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Technical Report

Higher-Strength Steel Weldments for
Submarine Hulls - Second Status Report

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Applied Research Laboratory
United States Steel

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HIGHER-STRENGTH STEEL WELDMENTS
FOR SUBMARINE HULLS—SECOND STATUS REPORT
(40.018-001)(39)(a-ORD-NP-3)(S-00000-1)

January 4, 1965

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Approved by W. T. Lankford, Jr., Assistant Director

Abstract

Since June 1, 1963, U. S. Steel has been engaged in the development of an HY-130/150 weldment and in a study of the feasibility of developing an HY-180/210 weldment under Bureau of Ships sponsorship. The progress of the programs was broadly reviewed on April 1, 1964, and is again reviewed in the present report.

The accomplishments to date in the HY-130/150 program indicate that a 5Ni-Cr-Mo-V steel has been developed that meets essentially all the requirements for an HY-140 steel. When the 5Ni-Cr-Mo-V steel was joined with a 140 ksi yield-strength 2Mn-2Ni MIG filler metal, the resulting weldments exhibited good performance in explosion tests. These tests also showed that when the yield strength of the weld metal matched or overmatched that of the base metal, the deformation characteristics of the weldments were satisfactory, whereas those of an undermatching weld metal were unsatisfactory.

Currently, 138 ksi is the typical yield strength for a reliable HY-130/150 type weld metal. Because this yield strength would match that of an HY-130 production plate (average yield strength of 138 ksi, range of 130 to 145 ksi), whereas it would undermatch that of an HY-140 plate, the interim objective for the HY-130/150 program should be the development of an HY-130 weldment for low-hull-fraction high-toughness combatant submarine hulls. Selection of an HY-130 weldment as an interim objective would facilitate initiation of the Weldment Evaluation Program (during January 1965) and of the Prototype Evaluation Program (during the latter part of 1965), and it would also facilitate an increase in the typical thickness of an HY-130/150 weldment if required. Nevertheless, the development of an HY-140 weldment will be pursued on a priority basis with the aim of replacing the HY-130 weldment at the earliest possible time.

Results of the HY-180/210 program indicate that the development of a 180 ksi minimum-yield-strength weldment having a Charpy V-notch energy absorption of about 50 ft-lb is feasible. However, a significant program including the development of improved steel compositions, low-residual melting practices, and special processing techniques for the base metal and filler metal will be required. Achievement of this toughness objective may not insure a weldment that will be "fracture tough" for large flaws and high stress concentrations. Therefore, the minimum acceptable "fracture toughness" should be established from studies of improved design, fabrication, and inspection practices.

Introduction

On June 1, 1963, Bureau of Ships Contract No. N0bs-88540 was initiated to develop a submarine-hull weldment with a yield strength in the range 130 to 150 ksi (SR007-01-01 Task 853) and to determine the feasibility of developing a submarine-hull weldment with a yield strength in the range 180 to 210 ksi (SS050-000 Task 1567). The starting points for the programs were broadly summarized in a preliminary status report.^{1)*} After 10 months work, the status of the programs was again reviewed in an interim status report.²⁾ As of December 1, 1964, eighteen months of the contract period have elapsed. Therefore, it appears appropriate to again review critically the accomplishments in terms of the program objectives and to project the final outcome of the program and the timetable therefor.

The objectives of the HY-130/150 program were established by projecting the performance requirements for an HY-80 weldment to those for an HY-130/150 weldment. By so doing, the requirements for a low-hull-fraction combatant HY-130/150 submarine hull would presumably be met. Thus, the accomplishments to date are being assessed in that context. For that reason, the conclusions and recommendations presented herein should not be applied to the less stringent requirements for a high-hull-fraction submarine or to the much less stringent requirements for noncombatant submersibles. Similarly, the feasibility of developing an HY-180/210 weldment is based on the low-hull-fraction combatant submarine concept.

*See References.

HY-130/150 Program

In accordance with the Contract outline, the following areas have been concurrently investigated.

Base-Metal Development

Laboratory evaluation of over 300 experimental compositions has led to the selection of a 5Ni-Cr-Mo-V steel of the composition shown in Table 1A. Table 1B shows that when this steel is properly quenched and tempered, the yield strength ranges from an average of 150 ksi for 1/2-inch-thick plate to 137 ksi for 4-inch-thick plate. When the steel is melted to the high side of the composition range, a minimum yield strength of 140 ksi is attainable in plates through 5 inches thick.

At 0 F, full shear fractures are obtained and the Charpy V-notch energy absorption ranges from 74 ft-lb for 4-inch-thick plate to 101 ft-lb for 1/2-inch-thick plate. For 1-inch-thick plate, the drop-weight tear energy absorption is 5000 to 6000 ft-lb, and the thickness can be reduced more than 40 percent by explosive deformation without fracture. Because the typical NDT is about -120 F, failure by brittle fracture will not be encountered at ice-water temperatures.

In the range 10,000 to 100,000 cycles, the strain to initiate fatigue cracks in the 5Ni-Cr-Mo-V steel is about the same fraction of its yield strain as that for HY-80 steel, Figure 1. When the 5Ni-Cr-Mo-V steel is welded by the inert-gas-shielded metal-arc (MIG) process using an

experimental HY-130/150 filler metal, the reduction in fatigue strength is of about the same magnitude as that for HY-80 steel when welded with an E11018 covered electrode. Thus, in the cycle life of primary interest, the fatigue design factors being used for HY-80 steel appear equally applicable to the 5Ni-Cr-Mo-V steel.

In sea-water corrosion tests, the 5Ni-Cr-Mo-V steel was slightly more resistant to general corrosion than HY-80 steel. In addition, the corrosion potential between the 5Ni-Cr-Mo-V steel and the experimental HY-130/150 MIG weld metal was less than that between HY-80 steel and the E11018 weld metal, Figure 2. No stress-corrosion failures have been observed in the 5Ni-Cr-Mo-V base metal or in the experimental MIG weld metal after 10 months exposure in a marine atmosphere or in sea water. In general then, the 5Ni-Cr-Mo-V weldment should be as resistant to various types of corrosion as an HY-80 weldment.

To date, three 80-ton heats of the 5Ni-Cr-Mo-V steel have been melted in standard electric furnaces using a conventional double-slag process, and the composition limits have been met with no particular problems. The desirability of melting the steel by the basic-oxygen process and by vacuum-consumable-electrode remelting is now being evaluated. In addition, the advantage of vacuum-carbon deoxidation after electric-furnace and after basic-oxygen melting is being assessed. The steel has normally been air-cast in the same size ingot molds as those used for HY-80 steel.

To date, most of the 5Ni-Cr-Mo-V steel production plates have been cross-rolled to a ratio of 3 to 1 or less. Laboratory studies indicate that directionality of properties can be satisfactorily minimized for cross-rolling ratios of 8 to 1 or lower, Table II. The limitations that this proposed maximum cross-rolling ratio may impose on production rates and plate sizes are now being developed. The 5Ni-Cr-Mo-V steel production plates have been heat-treated on conventional facilities with no special problems. Because the steel was designed to exhibit a constant yield strength when tempered in the range 900 to 1100 F, no difficulties have been encountered in producing the steel with a 15 ksi yield-strength range, Figure 3.

Several CB-103 structural sections of the 5Ni-Cr-Mo-V steel have been rolled with no apparent difficulty, and the properties after heat treatment were very attractive, Table III. A large ingot of the 5Ni-Cr-Mo-V steel was forged into a ring with no difficulty, and 5Ni-Cr-Mo-V steel castings as large as 500 pounds have been produced. The properties of the laboratory castings were quite satisfactory after heat treatment, Table IV. Cost estimates for producing a large 5Ni-Cr-Mo-V casting of the type used in HY-80 hulls have been received from approved HY-80 casting producers. The production and evaluation of one or more large 5Ni-Cr-Mo-V steel castings should establish the status of the casting development.

Although an exact price for 5Ni-Cr-Mo-V steel plates must await a specification based on additional production experience, the price will

probably be about that of HY-80 steel on a strength to weight basis. Trial orders for plates and shapes will now be accepted in accordance with normal delivery schedules.

Joining Development

The strength, toughness, crack susceptibility, and transformation characteristics of the heat-affected zone was a prime consideration in the development of the composition of the 5Ni-Cr-Mo-V steel. When the steel is welded over a wide range of practical heat inputs and preheat and interpass temperatures, the heat-affected-zone hardness is almost identical to that of the base metal. This is an improvement over HY-80 steel. With the same welding conditions, the heat-affected zone is essentially fully martensitic and the minimum Charpy V-notch energy absorption is about 80 ft-lb at 0 F, Figure 4. The heat-affected zone of the 5Ni-Cr-Mo-V steel, as measured in very critical laboratory tests, is about as resistant to restraint cracking as the most crack-resistant HY-80 steel, Table V. Thus, the procedures now employed to insure satisfactory heat-affected-zone properties in HY-80 steel weldments should be satisfactory for 5Ni-Cr-Mo-V steel weldments.

For the past year, over half the HY-130/150 program effort has been devoted to the development of filler metals and welding techniques. A MIG filler metal of the composition shown in Table VI has been developed that has exceptional toughness at an average yield strength of 136 ksi when deposited by spray transfer. Techniques have been developed so that similar properties

are obtained when this filler metal is deposited in the vertical or overhead position. To date, commercial quantities of this filler wire have not been produced because studies have been in progress to develop a higher-strength weld metal.

Evaluation of 2Mn-2Ni filler metals designed to exhibit weld-metal yield strengths over 140 ksi has shown that these weld metals are susceptible to cracking. Increases in preheat and interpass temperature have reduced the cracking but have also reduced the yield strength. For that reason, major modifications in the composition of experimental MIG filler metals are now being examined. Thus, the development of a practical MIG filler metal with a yield strength of 145 to 150 ksi is not expected for about 6 months. However, as discussed under Structural Evaluation, the present 138 ksi average-yield-strength weld metal may be suitable for an HY-130/150 weldment, at least on an interim basis. Therefore, a production heat of the 2Mn-2Ni MIG filler wire is being made.

Because preliminary tests of 5Ni-Cr-Mo-V weldments fabricated using covered electrodes were promising, development of experimental HY-130/150 covered electrodes has been continued on a high-priority basis and is being further accelerated. The best weld-metal properties that have been obtained to date when plates of the 5Ni-Cr-Mo-V steel were welded under practical conditions using covered electrodes are shown in Table VII.

Although the weld metal exhibits a relatively high yield strength, the toughness is lower than that desired. Explosion-deformation tests to evaluate the most promising compositions are planned for the immediate future. Final selection of the most promising covered electrode is scheduled for May 1965. Shortly thereafter, production quantities of the best HY-130/150 covered electrode should be available for full-scale evaluation.

Structural Evaluation

From Laboratory studies on the 5Ni-Cr-Mo-V and other high-yield-strength steels, a method has been devised for predicting the cold formability of steels from their tensile ductility. Laboratory forming of plates up to 1/2 inch thick and shipyard forming of plates up to 3-3/8 inches thick, Table VIII, have confirmed the prediction equation. The test results also showed that 5Ni-Cr-Mo-V steel plates have more than enough ductility to be cold-formed to radii much smaller than those required for submarine-hull fabrication. The effect of cold forming on the mechanical properties of heavy-gage 5Ni-Cr-Mo-V steel plates is currently being evaluated, and the results will be compared with those of a previously completed similar study on HY-80 steel.

A major study of the structural suitability of 5Ni-Cr-Mo-V steel plates and weldments has been planned as described in Appendix A. The study is intended to demonstrate the suitability of 5Ni-Cr-Mo-V weldments

for the fabrication of a prototype structure. The tests will be conducted by the Applied Science Laboratory, the Marine Engineering Laboratory, the Naval Research Laboratory, and the Contractor. This Weldment Evaluation Program is scheduled to be initiated around January 1, 1965. However, the program cannot be initiated until a filler metal meeting most of the ultimate requirements is selected. That selection, in turn, cannot be made until the yield-strength requirements for the filler metal as compared with those for the base metal have been defined.

To investigate the effect of yield-strength differences between the weld metal and base metal, 1-inch-thick plates of the 5Ni-Cr-Mo-V steel having nominal yield strengths of 130, 140, and 150 ksi were joined with a 2Mn-2Ni MIG weld metal having a nominal yield strength of 140 ksi. The weldments were explosively deformed by four 7-pound shots of pentolite. After each shot, the thickness reduction in the bulge area was measured. The results, Figure 5, showed that each of the weldments reduced in thickness 12 to 14 percent without cracking. This ability to deform extensively at high strain rates is extremely encouraging.

Figure 5 also shows that the thickness reduction of the base metal generally decreased as its yield strength increased, whereas the thickness reduction of the weld metal was about the same for the three weldments. Thus, in the maximum bulge area, Curve A shows that the weld

metal reduced or thinned less than the base metal because its yield strength was higher than that of the base metal, Curve B shows that the weld metal reduced about the same amount as the base metal because their yield strengths were about equal, and Curve C shows that the weld metal reduced more than the base metal because its yield strength was lower than that of the base metal. These results indicate that, to a limited extent, the deformation across the weld depends upon the relative yield strength of the base metal and the weld metal. In general, an undermatching weld metal (Curve C) is undesirable because the weld metal, which is usually less tough and ductile than the base metal, is deformed more than the base metal. However, the difference between the overmatching (Curve A) and matching (Curve B) conditions appears insignificant. In both instances the weld metal undergoes almost as much deformation as the base metal. Thus for the conditions studied, the deformation characteristics of a weldment with a matching filler metal are about as desirable as those of a weldment with an overmatching filler metal.

When applied to the 5Ni-Cr-Mo-V experimental HY-130/150 steel and experimental HY-130/150 MIG filler metals, the preceding observations indicate that a matching or overmatching weld metal is desirable when its ductility and toughness are about equal to those of lower-strength weld metal. Unfortunately, experimental overmatching weld metals have exhibited a high

susceptibility to cracking. Thus, at the present state of development, a matching 5Ni-Cr-Mo-V weldment will outperform an overmatching weldment at a base-metal yield strength of 140 ksi.

The explosion tests indicate that a satisfactory weldment having a yield strength of 140 ksi appears essentially developed. Although this is correct on an absolute-yield-strength basis, it is not correct on a minimum-yield-strength basis. To insure a minimum yield strength of 140 ksi, HY-140 plates would be produced to yield strengths in the range 140 to 155 ksi. Thus, to match the average yield strength of an HY-140 base metal, the yield strength of the weld metal should average about 148 ksi.

Currently, the yield strength of a high-reliability high-toughness weld metal is about 138 ksi. This weld metal would match the average yield strength (138 ksi) of HY-130 production plates (yield-strength range of 130 to 145 ksi). Thus, to facilitate work on the Weldment Evaluation Program, a 130 ksi minimum-yield-strength weldment is recommended as an interim objective. No difficulty is anticipated in lowering the yield-strength range for the 5Ni-Cr-Mo-V steel from 140 to 155 ksi down to 130 to 145 ksi. However, studies to develop weld metals having higher yield strengths would be continued at the current rate of effort so that the minimum yield strength could be set at 140 ksi when the higher-strength weld metals become available.

Setting the minimum-yield-strength objective for an HY-130/150 weldment at 130 ksi would also facilitate an increase in the plate-thickness

objectives from the present average and maximum thickness of 2 and 4 inches, respectively. The composition of the 5Ni-Cr-Mo-V steel was carefully designed so that the optimum combination of mechanical properties and weldability was obtainable in 2-inch-thick plates, the thickness of primary interest. Thus, the mechanical properties of 3- to 4-inch-thick plates are somewhat lower than those of the 2-inch-thick plates. This loss has not been considered important because the heavy plates are used in noncritical locations or the components are designed to compensate for the lower properties. If, however, the interest in increasing thickness continues and 3- to 4-inch-thick plates represent the thickness of primary interest, adjustments in the composition of the 5Ni-Cr-Mo-V steel should be made so that the optimum combination of mechanical properties and weldability is obtainable in 3- to 4-inch-thick plates. Much more development work would be required to make the required composition adjustments at a minimum yield strength of 140 ksi than at a minimum yield strength of 130 ksi. For that reason, the program to evaluate the structural suitability of weldments having a minimum yield strength of 130 ksi, including heavy-gage weldments, could be initiated without significant delay, whereas some delay is anticipated in initiating a similar program for 140 ksi minimum-yield-strength weldments.

Finally, the higher toughness that has been observed for the 5Ni-Cr-Mo-V steel at a yield strength of 130 ksi compared with that at a yield strength of 140 ksi (102 ft-lb versus 80 ft-lb for 2-inch-thick plate) may be desirable, particularly for the very heavy plates required. This

observation is based on the amount of base-metal shear tearing that has occurred in explosion-bulge tests of 140 to 150 ksi yield-strength 5Ni-Cr-Mo-V weldments. Despite the very high toughness of the 5Ni-Cr-Mo-V steel compared with the minimum objective of 50 ft-lb, the shear tearing is much greater than in HY-80 steel. This is not unexpected inasmuch as the stored elastic energy to propagate cracks is much higher in the 5Ni-Cr-Mo-V steel than in the HY-80 steel, whereas the shear energy absorption of the 5Ni-Cr-Mo-V steel at a minimum yield strength of 140 ksi is lower than that of HY-80 steel at a minimum yield strength of 80 ksi. (When HY-80 steel is heat-treated to a yield strength of 140 ksi, its shear energy absorption is only about one half that of the 5Ni-Cr-Mo-V steel at the same yield strength.) Although the resistance of HY-80 steel to shear-crack propagation may be greater than that required for a "fracture-tough" design, the higher toughness of a 130 ksi compared with a 140 ksi minimum-yield-strength 5Ni-Cr-Mo-V steel may ultimately be desirable for the low-hull-fraction high-toughness combatant submarine.

For high-hull-fraction submarines and for noncombatant submersibles, the preceding discussions are probably not applicable. In fact, undermatching weld metals are believed to be quite satisfactory because the total strain imposed upon the weld metal, even in areas of high strain concentration, is far less than that produced in explosion tests. Thus, submersibles of this type fabricated from the 5Ni-Cr-Mo-V steel could probably be designed to a minimum yield strength of 140 ksi and higher.

Prototype Evaluation

If the minimum yield strength for an HY-130/150 weldment is set at 130 ksi, at least on an interim basis, the Weldment Evaluation Program can probably be completed in time to initiate the Prototype Evaluation Program during the latter part of 1965.

HY-180/210 Program

Because the HY-180/210 program is a feasibility study, which would be followed by a development study, the progress of the program can best be assessed by evaluating the probability of successfully developing the approaches that have been investigated.

Base-Metal Development

Three different alloy-steel systems have been systematically investigated to determine their potential as HY-180/210 base metals—(1) conventional quenched and tempered carbon-martensitic steels, (2) very low-carbon maraging steels, and (3) carbon-martensitic precipitation-hardened steels. The strength-toughness relations that have been exhibited by 1/2-inch-thick plates from laboratory heats of the various steels are summarized in Figure 6. The summary shows that maraging steels consistently exhibit the best combinations of strength and toughness.

The optimum trend line in Figure 6 shows that for the current state of development, the highest toughness is about 64 ft-lb at a yield

strength of 185 ksi, the lowest-aim yield strength for production plates to insure a minimum yield strength of 180 ksi. The trend line also shows that the toughness decreases about 1 ft-lb for every 1 ksi increase in the yield strength. The optimum trend line is based on the properties of laboratory heats that were melted in vacuum so that the interstitial gas content (O_2 , H_2 , and N_2) and the metalloid content (C, P, and S) were very low. In addition, the small laboratory ingots solidified much more rapidly than large production ingots and thereby minimized segregation and the size of the ingot dendrites. When heats of the 12Ni-5Cr-3Mo steel were melted in air in a 20-ton electric furnace and air-cast into 32- by 60-inch, 20-ton ingots, the properties fell significantly below the optimum trend line, Figure 7. At this time, the relative effects on mechanical properties of steel purity as controlled by melting practice and of segregation and ingot structures as controlled by ingot size are not known. Large-size heats of the 12Ni-5Cr-3Mo steel are now being melted by various low-residual-element practices so that the effect of melting practice can be assessed for large heats and ingot sizes.

As discussed herein under the HY-130/150 program, resistance to shear-crack propagation undoubtedly decreases as yield strength increases at a constant toughness because of the increase in the stored elastic energy with increasing yield strength. Thus, the development of melting practices for large heats that would insure consistent attainment of the

optimum trend line in production plates may not assure fracture-tough behavior in large fabricated structures. For that reason, research must be continued on alloy systems that are inherently tougher than those developed to date. In addition, work should be continued on melting practices that may lead to even lower residual-element levels in high-yield-strength steels with the objective of further increases in toughness.

Figure 7 also shows that the toughness of the 12Ni-5Cr-3Mo steel is significantly lowered as the plate thickness increases. The same effect is expected for all alloy systems at a yield strength in the range 180 to 210 ksi. To confirm this observation, heavy plates rolled from production heats of the most promising quenched and tempered steel and of the most promising carbon-martensitic precipitation-hardened steel will be evaluated. Because the thick plates that are required for combatant and noncombatant submersibles appear to exhibit much lower toughness than thin plates, methods of minimizing or eliminating this effect must be devised. Figure 8 shows that the loss in toughness in thick plates can be minimized in the 12Ni-5Cr-3Mo steel by forging rather than rolling the plates. Forging increased the amount and depth of hot work and decreased the temperature range of hot working, thereby increasing the toughness of thick plates. Further work on special hot-working techniques will be required.

Improvements in properties that can be achieved by other special processing techniques must be explored. One extremely promising technique

that was originated about 4 years ago at the Applied Research Laboratory is being intensively examined in the HY-180/210 program. The technique involves rapid heating during austenitizing to produce a very-fine-grain, heterogeneous austenite. When conventional carbon-martensitic steels are austenitized in this way, very significant improvements in the strength-toughness combinations have been obtained, as illustrated in Figure 9 for the 5Ni-Cr-Mo-V steel. Studies are now being planned to determine (1) the maximum plate thickness at which such improvements can be obtained, (2) the applicability of rapid heat treatment to alloy systems other than quenched and tempered steels, (3) the effect of the composition of quenched and tempered steels on response to rapid heat treatment, and (4) the feasibility of designing and constructing production facilities for rapid heat treatment of large thick plates. Work on this and other special processing techniques should be accelerated.

The development of improved HY-180/210 alloy systems, improved low-residual melting and casting techniques, improved methods of hot working, and special processing techniques such as rapid heat treatment may not insure the development of plates that can be fabricated into a fracture-tough structure. Therefore, studies should be initiated to establish the extent to which improved design, fabrication, and inspection can reduce fracture-toughness requirements. At present, submarine hulls are fabricated from weldments that are tough enough so that large flaws

and high stress concentrations do not cause crack extension until stresses close to the ultimate tensile strength are imposed. Inevitably, a yield strength will be reached at which the steel will no longer exhibit fracture-tough behavior as previously defined. At present, steels do not exhibit this type of fracture toughness at a minimum yield strength of 180 ksi. Thus, designs for submersibles will eventually be required that minimize stress concentrations and in which the stress concentrations caused by geometric discontinuities or "hard spots" can be accurately analyzed. Fabrication techniques that minimize or eliminate stress concentrations, residual stresses, and flaws must be developed, evaluated, and applied. Finally, inspection techniques must be devised, evaluated, and utilized that will detect all flaws larger than those that will propagate catastrophically in material of a given fracture toughness.

As was previously observed, stress corrosion is not expected to be a problem in the HY-130/150 steels. However, significant susceptibility to stress corrosion has been observed in quenched and tempered steels having yield strengths over 200 ksi. Thus, the yield strengths of HY-180/210 steels lie in a "gray area" where stress corrosion may or may not be a problem. Preliminary tests indicate that the 12Ni-5Cr-3Mo base metal may also be susceptible to stress corrosion and that the experimental filler metals developed to date for the 12Ni-5Cr-3Mo steel probably are susceptible to stress corrosion, Figure 10. Thus, the 180 to 210 ksi

yield-strength range appears to be a "gray area" for stress corrosion of martensitic steels. The factors influencing stress corrosion of steels in this yield-strength range are being intensively investigated with the aim of developing composition or processing modifications that will eliminate stress-corrosion susceptibility. Preliminary results indicate that fine-grain steels are much more resistant to stress corrosion than coarse-grain steels. Thus, the ultrafine grain size produced by rapid heat treatment may eliminate stress corrosion in experimental HY-180/210 steels. However, consideration should be given to systems for protecting the weld metal and possibly the base metal in HY-180/210 submersibles.

Joining Development

Because some experience with the production of the 12Ni-5Cr-3Mo steel was available at the time the Contract was initiated, the weldability and filler-metal development in the HY-180/210 feasibility study have been concentrated on maraging steels. Studies of the heat-affected-zone properties of the 12Ni-5Cr-3Mo steel have shown that the steel is reasonably resistant to restraint cracking and that the strength and toughness of the heat-affected zone can be restored to essentially that of the base metal by a 900 F postweld aging treatment, Table IX.

Numerous filler metals of the 12Ni-5Cr-3Mo type have been evaluated when deposited by the MIG and TIG processes. In general, no difficulty has been encountered in fabricating sound joints or in obtaining

the desired weld-metal yield strength. However, as shown in Figure 11, the toughness of the weld metals, particularly those deposited by the MIG process, is rather low. The optimum trend line indicates that a toughness close to 50 ft-lb at a yield strength of 185 ksi should be attainable with the 12Ni-5Cr-3Mo type filler metals after suitable additional development work. Figure 11 also shows that several carbon-martensitic precipitation-hardening weld metals exhibit strength and toughness combinations close to the optimum trend line. Thus, there is reason to believe that HY-180/210 filler metals will ultimately be developed that will be almost as tough as an HY-180/210 base metal. Moreover, the loss in toughness that is observed when the thickness of the base metal is increased is not a factor in the toughness of the weld metal, inasmuch as the weld metal is deposited in essentially the same way regardless of the plate thickness.

As was observed for the HY-180/210 base metal, an energy absorption of 50 ft-lb for an HY-180/210 weld metal may not insure a "fracture-tough" structure. Therefore, the comments concerning the need for studies of improved design, fabrication techniques, and inspection techniques to minimize toughness requirements for HY-180/210 base metals apply equally to HY-180/210 weld metals.

The results of the HY-180/210 study indicate that it is feasible to develop steel weldments having yield strengths in the range 180 to 210 ksi that exhibit base-metal and weld-metal Charpy V-notch energy absorptions

of about 50 ft-lb. However, the base metal will undoubtedly be melted to very low residual-element levels, and the ingots will be processed to plates by special techniques. In addition, other special processing techniques will probably be employed to insure a consistently high toughness. Similarly, the filler metals will probably be produced to very low residual-element levels, drawn to wire by special techniques, and deposited only by processes that insure retention of the high purity. To succeed in this undertaking, a significant development program will be required.

Initially, the cost of a high-toughness HY-180/210 weldment will be high. However, the material, fabrication, and inspection costs should decrease steadily as experience in this frontier area is gained.

References

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APPENDIX

-23-

UNITED STATES STEEL

APPENDIX A

Proposed Weldment Evaluation Program for 5Ni-Cr-Mo-V Steel

I. Welding Procedure Study—Part I (U. S. Steel)

- A. Purpose: To define limits of plate thickness and preheat temperature within which suitable mechanical properties and soundness can be achieved.
- B. Test Outline: Experimental weldments will be fabricated as follows:

<u>Plate Thickness, inches</u>	<u>Welding Process</u>	<u>Preheat and Interpass Temperature, F</u>
1/2	Covered Electrode	150, 200, 250, 300
1/2	MIG	150, 200, 250, 300
1	Covered Electrode	150, 200, 250, 300
1	MIG	150, 200, 250, 300
2	Covered Electrode	150, 200, 250, 300
2	MIG	150, 200, 250, 300

C. General Test Conditions

1. All weldments to be 18 inches wide by 18 inches long.
2. All weldments to be radiographed and tested in the as-welded condition.
3. Welding heat input:
 - a. MIG - 1/16-inch-diameter electrode - 60,000 $\pm$ 5000 joules/inch.
 - b. MIG - 0.045-inch-diameter electrode - 45,000 $\pm$ 5000 joules/inch.

(Continued)

APPENDIX A (Continued)

Proposed Weldment Evaluation Program for
5Ni-Cr-Mo-V Steel (Continued)

- c. Covered Electrode - 3/16-inch diameter - 45,000 $\pm$ 5000 joules/inch.
- d. Covered Electrode - 5/32-inch diameter - 30,000 $\pm$ 5000 joules/inch.
- 4. Joint Geometry - 1/2-inch-thick plate - 60° single Vee, 1- and 2-inch-thick plate - 60° double Vee.
- 5. MIG shielding gas = A + 20₂ at 50 cu ft per hour.
- 6. Covered-electrode conditioning: All electrodes baked at 800 F for one hour and stored at 250 F prior to use.
- 7. Mechanical-property tests:
 - a. All-weld-metal 0.252-inch-diameter tension tests.
 - b. Charpy V-notch impact tests at +80 F, 0 F, and -60 F.
 - c. AWS side-bend tests.
 - d. Transverse plate-type tension tests (Fig. 2, MIL-STD-418).

II. Welding Procedure Study—Part II (U. S. Steel)

- A. Purpose: To determine effects of stress relieving on weld-metal mechanical properties.
- B. Experimental Procedure:
 - 1. Two weldments - 1 inch by 12 inches by 40 inches (40-inch weld) - one to be fabricated by the MIG process, the other by the covered-electrode process. The welding conditions to be determined from results of Part I.

(Continued)

APPENDIX A (Continued)

Proposed Weldment Evaluation Program for
5Ni-Cr-Mo-V Steel (Continued)

2. Test conditions:

- a. As-welded.
- b. 1025 F for 1 hour, slow-cool at 50 F per hour.
- c. 1025 F for 1 hour, accelerated air-cool.
- d. 1025 F for 1 hour, accelerated air-cool, repeat for 10 cycles.
- e. 1025 F for 100 hours, accelerated air-cool.

3. Mechanical-property tests:

- a. All-weld-metal 0.252-inch-diameter tension tests.
- b. Charpy V-notch impact tests at +80 F, 0 F, and -60 F.

III. Welding Procedure Study—Part III (U. S. Steel)

- A. Purpose: To determine relation between weld cracking and preheat and interpass temperature.
- B. Test Outline: The following specimens will be fabricated with both the MIG and covered-electrode welding processes. The welding conditions will be determined by results of Part I.
 - 1. Electric Boat frame-to-hull specimen:
 - a. 200 F preheat and interpass temperature, inspect in as-welded condition.

(Continued)

APPENDIX A (Continued)

Proposed Weldment Evaluation Program for 5Ni-Cr-Mo-V Steel (Continued)

- b. Preheat and interpass temperature based on results of first specimen, inspect in as-welded condition.
 - c. Preheat and interpass temperature that does not produce weld cracks in as-welded condition, inspect in stress-relieved condition.
2. Lehigh restraint-cracking-test specimen:
- a. Single-pass welds with different restraint at 78 F.
 - b. Single-pass welds with different preheat temperatures.
 - c. Double-pass welds with different preheat temperatures.

IV. Fracture-Toughness Studies

A. U. S. Steel:

- 1. Drop-weight tear tests (1-inch- and 2-inch-thick plates).
- 2. Drop-weight bulge tests (1/2-inch plain plates and weldments).
- 3. Plain-strain K_{IC} tests (1-inch- and 2-inch-thick plates).

B. NRL:

- 1. Drop-weight tear tests (1-inch- and 2-inch-thick plates).
- 2. Drop-weight bulge tests (1-inch- and 2-inch- (if possible) thick plain plates and weldments):
 - a. Plain plates (NDT, FTE, FTP).

(Continued)

APPENDIX A (Continued)

Proposed Weldment Evaluation Program for
5Ni-Cr-Mo-V Steel (Continued)

- b. Weldments (with and without crack starter):
 - 1. MIG and covered electrode.
 - 2. As-welded plus stress-relieved.
 - 3. Selected preheat and interpass temperatures, and heat inputs based on results of welding procedure studies.
 - c. Matching, undermatching, overmatching:
 - 1. +30 F with photogrid.
 - 2. 140 ksi weld metal.
 - 3. 130, 140, 150 ksi base metal.
 - 3. Explosion-deformation tests (1-inch-thick plain plates and weldments - conditions same as those used for drop-weight bulge tests).
 - 4. Explosion-tear - establish flaw size - deformation relationships.
- C. ASL:
- 1. Explosion-bulge weldment tests (2-inch-thick):
 - a. MIG and covered electrode
 - b. As-welded plus stress-relieved.
 - c. Welding conditions based on results of welding procedure studies.

(Continued)

APPENDIX A (Continued)

Proposed Weldment Evaluation Program for
5Ni-Cr-Mo-V Steel (Continued)

V. Fatigue Studies

A. U. S. Steel:

1. Cantilever beam - plain plate and weldments.
2. MIG and covered electrode.
3. Surface conditions (smooth, notched, sand-blasted).
4. Air and synthetic sea water.
5. Strain ranges to produce failure between 10^2 and 10^5 cycles.

B. NRL:

1. Rate of fatigue-crack-propagation tests.

C. MEL:

1. Welded box tests.
2. Programmed axial tests.

D. ASL:

1. Large plate tests.
2. Large plates with fillet welds.

E. University of Illinois - Axial tests (limited number of tests to be conducted as part of existing Bureau of Ships contract with University of Illinois):

(Continued)

APPENDIX A (Continued)

Proposed Weldment Evaluation Program for
5Ni-Cr-Mo-V Steel (Continued)

1. Plain-plate specimens.
2. Transverse butt-weld specimens.

VI. Corrosion Studies (U. S. Steel)

- A. Stress-corrosion (U-bend, 16 percent strain plus yield-stress loading), galvanic-corrosion, and general-corrosion specimens.
- B. MIG and covered-electrode weldments.
- C. Exposure - Wrightsville Beach and Kure Beach, N. C.:
 1. Flowing sea water.
 2. Nonflowing sea water - total immersion.
 3. Nonflowing sea water - periodic immersion.
 4. Marine atmosphere - 80-foot lot.

Table I

Typical Properties of 5Ni-Cr-Mo-V Steel

A. Chemical Composition—Percent

	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>V</u>	<u>sol. Al</u>
Range	$\frac{0.08}{0.13}$	$\frac{0.65}{0.90}$	0.010 max	0.010 max	$\frac{0.20}{0.35}$	$\frac{4.80}{5.30}$	$\frac{0.45}{0.65}$	$\frac{0.47}{0.62}$	$\frac{0.04}{0.07}$	$\frac{0.015}{0.040}$
Min	0.10	0.75	LAP	LAP	0.30	5.00	0.55	0.55	0.06	0.025

B. Midthickness Mechanical Properties

Plate Thickness, inches	Specimen Orientation	Yield Strength (0.2% Offset), ksi	Elongation in 1 Inch, %	Charpy V-Notch Energy Absorption at 0 F, ft-lb
1/2	Longitudinal	149	20.0	101
	Transverse	151	19.5	91
4	Longitudinal	137	19.5	77
	Transverse	137	19.5	74

(40.018-001) (39)

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Table II

Typical Effects of Laboratory Hot Rolling on Properties of
1-Inch-Thick 5Ni-Cr-Mo-V Steel

Rolling Condition	Tensile Yield Strength, ksi			Charpy V-Notch Energy Absorption at 0 F., ft.-lb		
	Strong*	Weak**	Difference	Strong	Weak	Difference
Straightaway-rolled	145	145	0	110	59	51
16 to 1 T/L	143	142	1	108	58	40
8 to 1 T/L	144	142	2	92	71	21
4 to 1 T/L	150	149	1	96	78	18
1.6 to 1 T/L	139	141	-2	95	83	12
1.6 to 1 L/T	145	144	1	98	78	20
1 to 1 L/T	143	145	-2	92	83	9

*Direction of maximum rolling.

**Direction of minimum rolling.

(40.018-001) (39)

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Table III

Mechanical Properties of CB-103 Beam of 5Ni-Cr-Mo-V Steel
(Heat No. X53957)

<u>Position</u>	<u>Orientation</u>	<u>Yield Strength (0.2% Offset), ksi</u>	<u>Elongation in 1 Inch, %</u>	<u>Charpy V-Notch Energy Absorption at 0 F., ft.-lb</u>
Flange	Longitudinal	150	20.0	90
	Transverse	147	20.0	52
Web	Longitudinal	145	20.5	92
	Vertical	146	19.0	65
Junction of Flange and Web	Longitudinal	146	19.5	89

NOTE: Beam section was austenitized for 1 hour at 1500 F., water-quenched and tempered for 1 hour at 1070 F. and water-quenched.

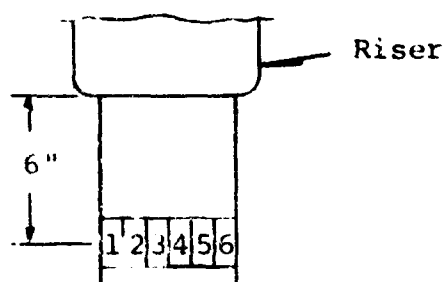
(40.018-001) (39)

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Table IV

Mechanical Properties of 5Ni-Cr-Mo-V Cast Steel Plate

Test Specimens were located
at Mid-Length of 4- by 12- by 12-Inch-Plate Casting



<u>Specimen Location</u>	<u>Yield Strength (0.2% Offset), ksi</u>	<u>Elongation in 1 Inch, %</u>	<u>Charpy V-Notch Energy Absorption at 0 F, ft-lb</u>
1	147	6.0*	71
2	147	18.0	73
3	148	17.0	75
4	148	17.0	76
5	147	18.0	66
6	147	17.0	65

*Sand inclusion.

NOTE: Casting was homogenized at 1700 F and water-quenched.
Austenitized at 1500 F, 2 hours, water-quenched.
Tempered at 1080 F, 2 hours, water-quenched.

(40.018-001) (39)

Table V

Results of Cruciform Restraint-Cracking Tests on 1/2-Inch-Thick Plates
of 5Ni-Cr-Mo-V Steel (X53185) and HY-80 Steel (X51289)

Steel	Filler Metal	Specimen No.	Weld-Heat-Affected-Zone Root Cracking, percent of weld length			
			Fillet A	Fillet B	Fillet C	Fillet D
5Ni-Cr-Mo-V	E11018-G	1	0	0	0	0
		2	0	0	0	0
		3	0	0	10	0
		4	0	0	0	0
		5	0	0	0	0
		Avg	0	0	2	0
HY-80	E11018-G	1	0	0	0	0
		2	0	0	0	0
		3	25	0	0	0
		4	0	0	0	0
		5	0	0	0	0
		6	0	0	0	0
		7	8	0	0	0
		8	8	0	0	0
		9	0	0	0	0
		10	0	0	0	0
		Avg	4	0	0	0

NOTE: All specimens were welded with a 78 F preheat and inter-pass temperature.

(40.018-001) (39)

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Table VI

Chemical Composition and Mechanical Properties of MIG Welding Wire

<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>	<u>Ti</u>
0.10	1.90	0.006	0.006	0.40	2.00	0.75	0.55	0.015
<u>Tensile Properties</u>								
<u>Yield Strength (0.2% Offset), ksi</u>	<u>Tensile Strength, ksi</u>	<u>Elongation in 1 Inch, %</u>	<u>Reduction of Area, %</u>	<u>Charpy V-Notch Energy Absorption, ft-lb</u>				
				<u>+80 F</u>	<u>0 F</u>	<u>-60 F</u>		
138	153	13.0	38.0	113	107	82		

(40.018-001) (39)

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Table VII

Mechanical Properties of 2Mn-2Ni Covered-Electrode Weld Metal

Yield Strength (0.2% Offset), ksi	Tensile Properties			Charpy V-Notch Energy Absorption, ft-lb			
	Tensile Strength, ksi	Elongation in 1 Inch, %	Reduction of Area, %	+75 F	+30 F	0 F	-60 F
144	165	18.0	51.0	35	31	29	21

(40.018-001) (39)

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Table VIII
Comparison of Predicted and Observed
Minimum Bend Radii for 5Ni-Cr-Mo-V Steel

<u>Plate Thickness, inches</u>	<u>Predicted Minimum Inside Bend Radius, inches</u>	<u>Actual Inside Bend Radius at Cracking, inches</u>
1/4	0.4	Between 0.19 and 0.34
3/8	0.7	Between 0.23 and 0.53
1/2	0.9	Between 0.78 and 0.94
1	1.8	<1.8
2	3.6	3.1
3-3/8	6.1	<5.1

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Table IX

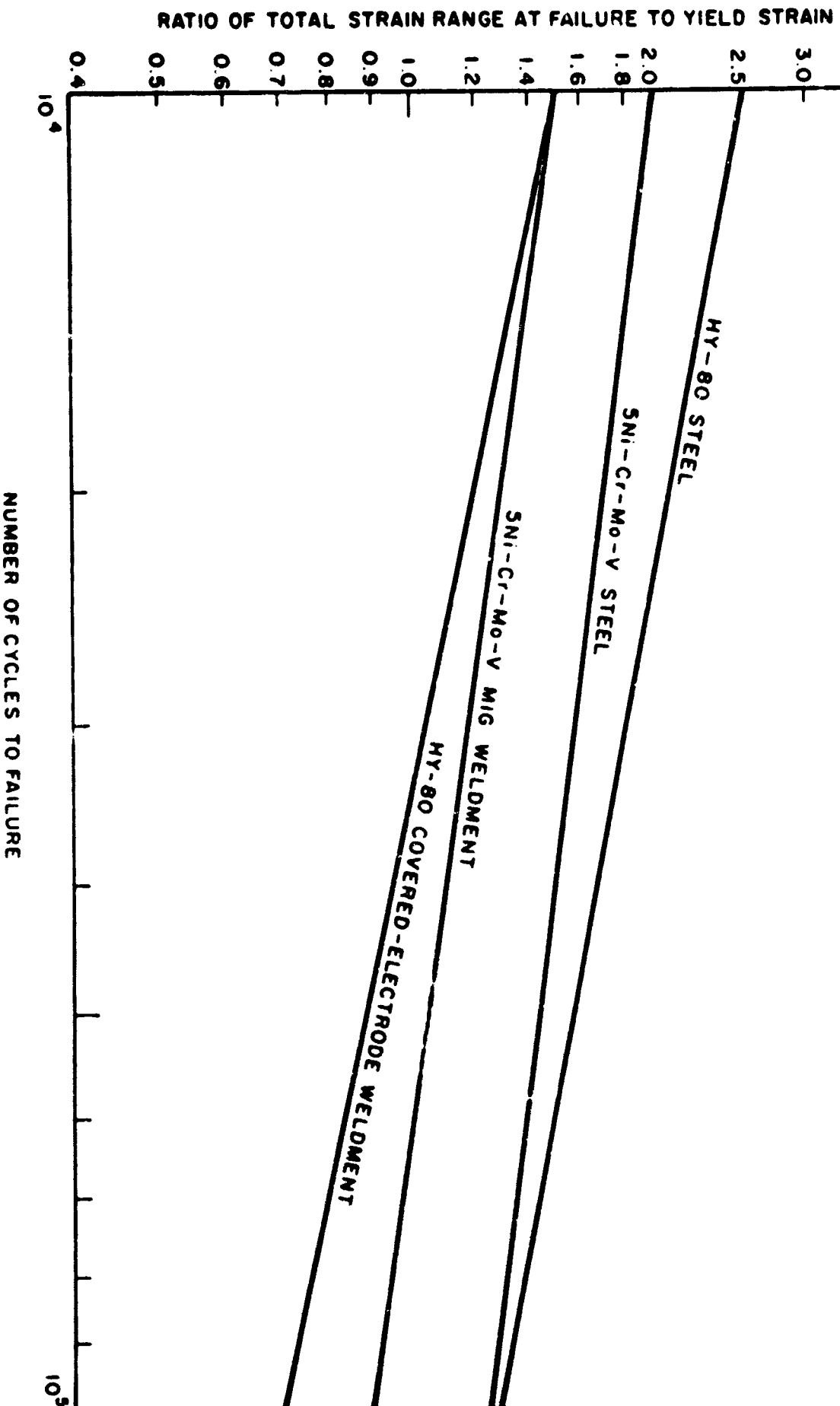
Mechanical Properties After Aging of Synthetic Heat-Affected-Zone Microstructures
of 12Ni-5Cr-3Mo Maraging Steel (Heat No. X14687)

Peak Temp, F	Tensile Properties		Fracture Location*	Charpy V-Notch Energy Absorption, ft-lb	
	Yield Strength (0.2% Offset), ksi	Elongation in 1 Inch, %		+80 F	0 F
2400	185	13.2	HAZ	39	36
2000	191	13.0	HAZ	36	33
1600	202	12.5	BM	31	32
1400	198	13.5	HAZ	36	33
1300	199	11.5	BM	35	31
1200	196	12.8	HAZ	41	39
1100	198	11.8	HAZ	33	34
1000	200	13.5	BM	33	34
Unaffected Base Metal	190	13.5	---	45	43

* HAZ means heat-affected zone;
BM means base metal.

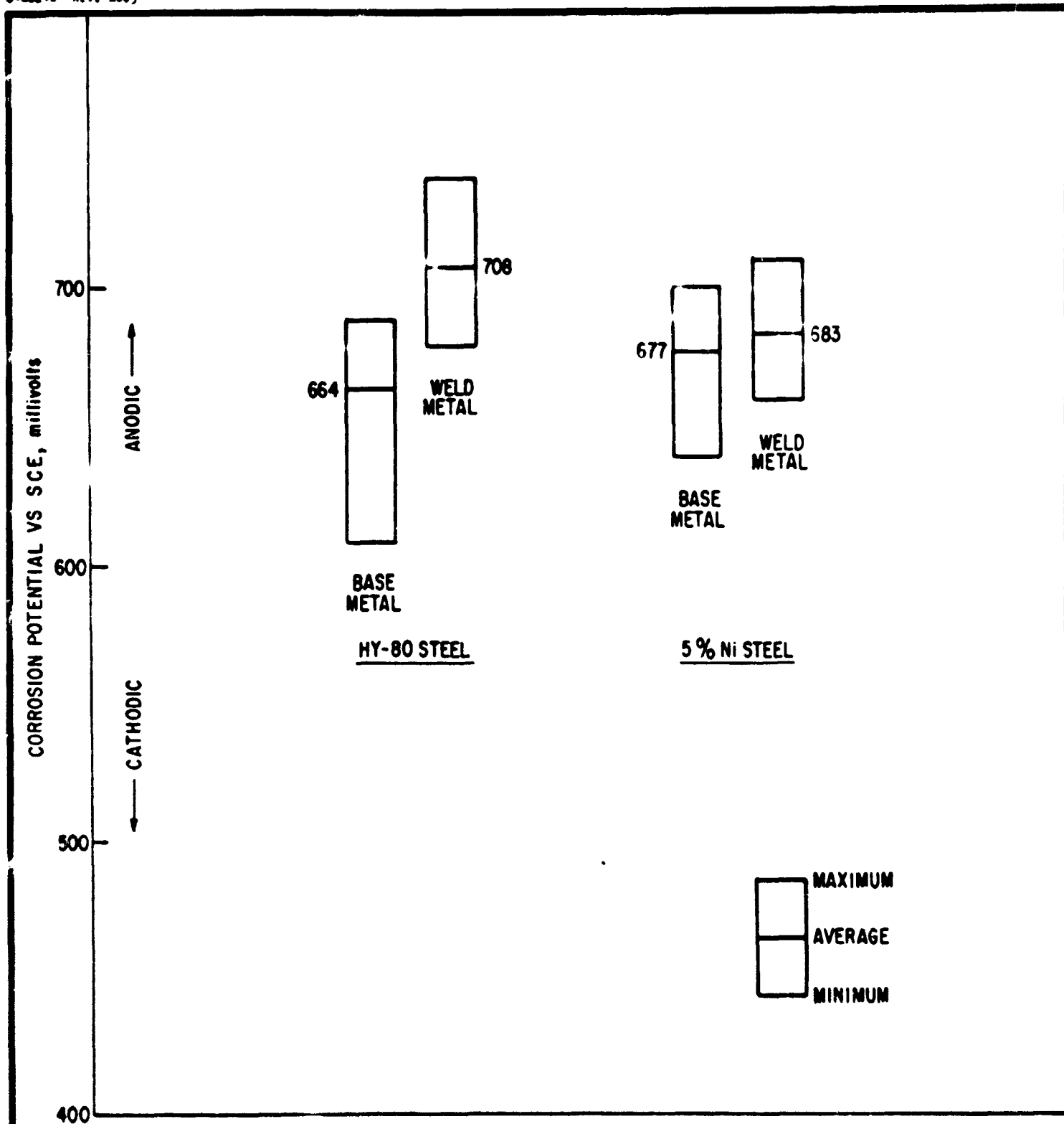
(40.018-001) (39)

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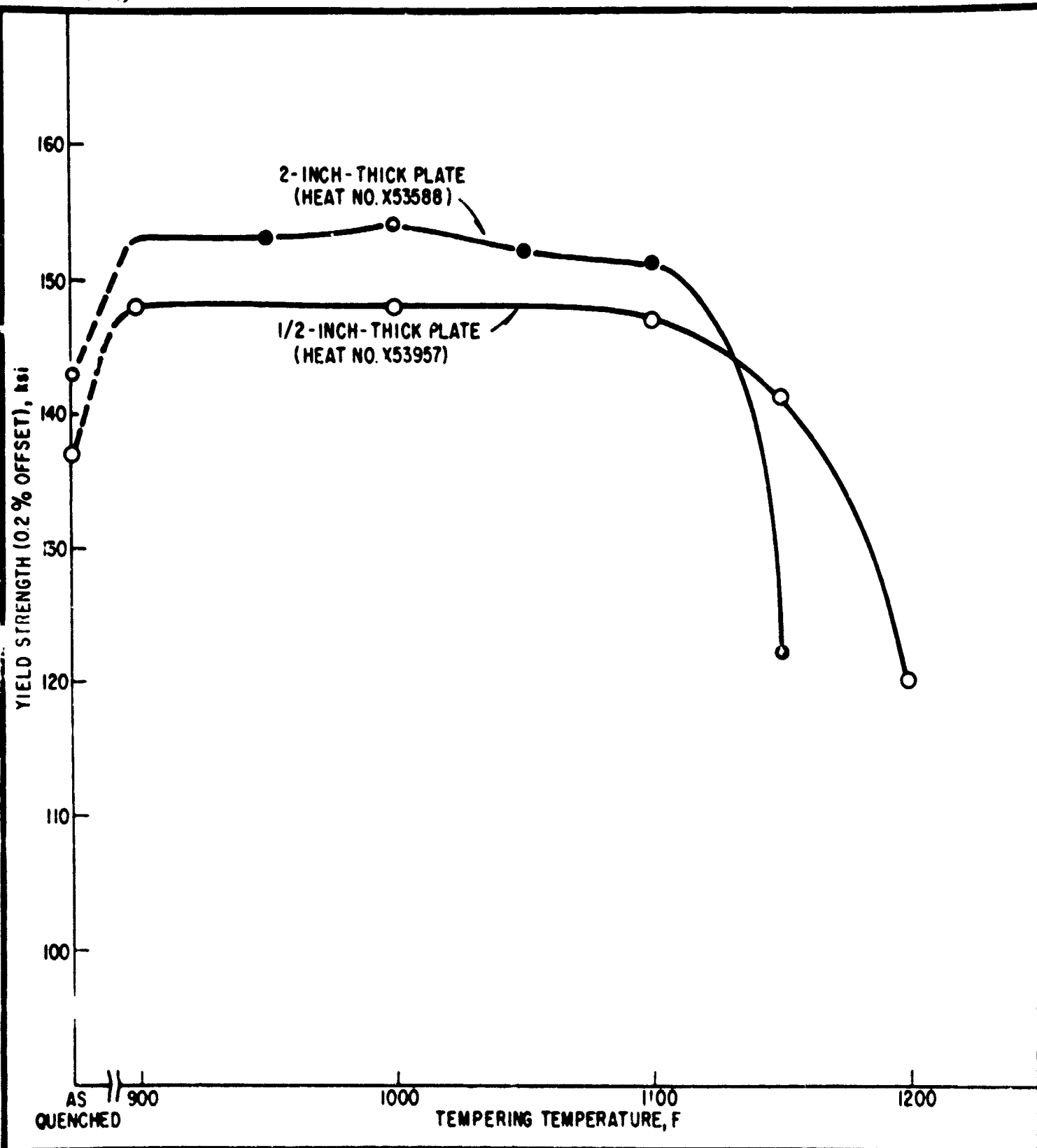
FATIGUE BEHAVIOR OF HY-80 AND 5Ni-Cr-Mo-V STEELS AND WELDMENTS
ON A YIELD-STRAIN BASIS

DRAWN BY: CHFD Bv		APPROVED BY: J H G		UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 1
G A Z		DSD			
DRAWING NO.		PROJECT NO.			
ARL 18-491		40 018-001 (39)			
		DATE: 11-25-64			



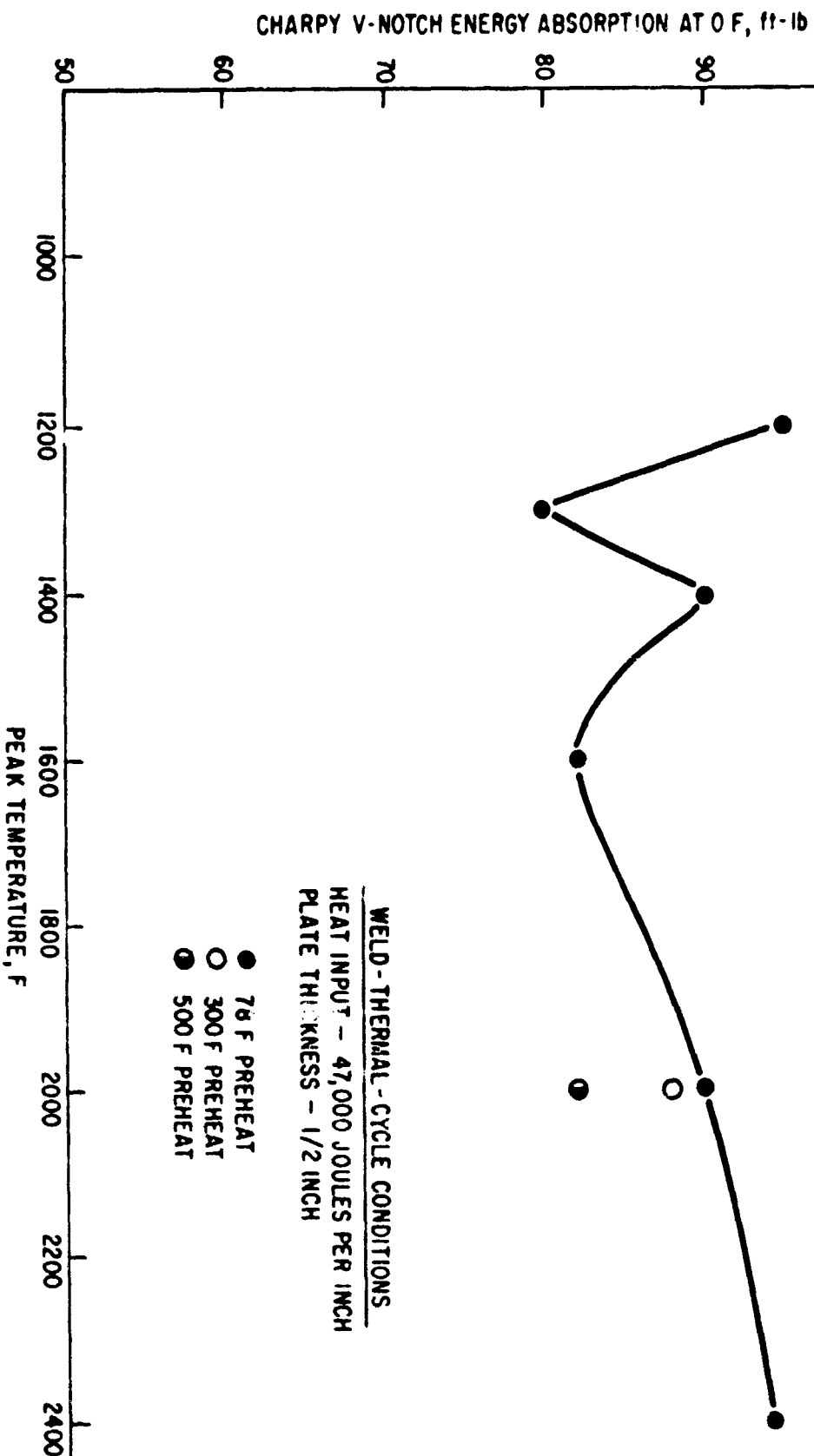
**CORROSION POTENTIALS OF HY-80 STEEL AND 5 Ni-Cr-Mo-V STEEL
IN SYNTHETIC SEA WATER AT ROOM TEMPERATURE**

DRAWN BY M.M.	CHK'D BY D.S.D.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 2
DRAWING No ARL 18-492		PROJECT No 40.018-001(39)		
		DATE 11/28/64		



TEMPERING CURVES FOR 1/2- AND 2-INCH-THICK PLATES OF 5Ni-Cr-Mo-V STEEL (MIDTHICKNESS LONGITUDINAL PROPERTIES)

DRAWN BY M.M.	CHK'D BY S.J.M.	APPROVED BY J.N.S.	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 3
DRAWING No ARL 18-484		PROJ. CT No 40.818-0013M		
		DATE 11/24/64		



CHARPY V-NOTCH ENERGY ABSORPTION OF VARIOUS REGIONS IN THE
 WELD - HEAT-AFFECTED ZONE OF 5 Ni-Cr-Mo-V STEEL (HEAT NO. X53185)

DRAWN BY CHM BY
 M.M. S.J.M.

APPROVED BY
 J.M.G.

DRAWING NO.

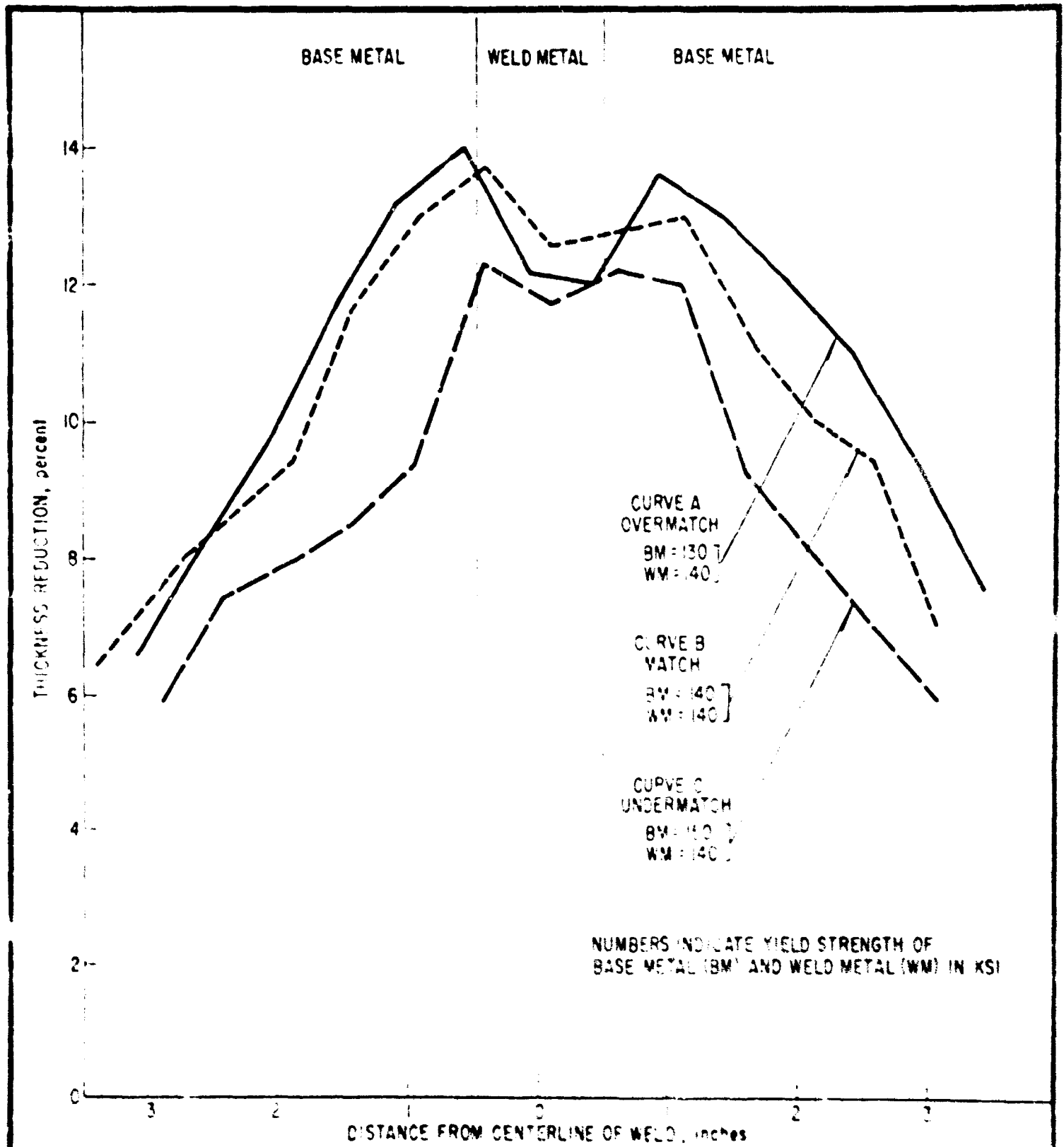
PROJECT NO.
 40.018 - 001 (39)

ARL 18-493

DATE
 11/24/64

UNITED STATES STEEL CORPORATION
 APPLIED RESEARCH
 PITTSBURGH, PA.

FIGURE
 NO.
 4



EFFECT OF DIFFERENCE IN YIELD STRENGTH OF 5 Ni-Cr-Mo-V STEEL AND
2.25-2 Ni MIG WELD METAL ON EXPLOSION-DEFORMATION CHARACTERISTICS

DRAWN BY
BY

CHECKED BY
JUM

APPROVED BY
JMG

DRAWING NO.

ARL 18-494

PROJECT NO.
40 C 8-001 (39)

DATE
11/24/64

UNITED STATES STEEL CORPORATION

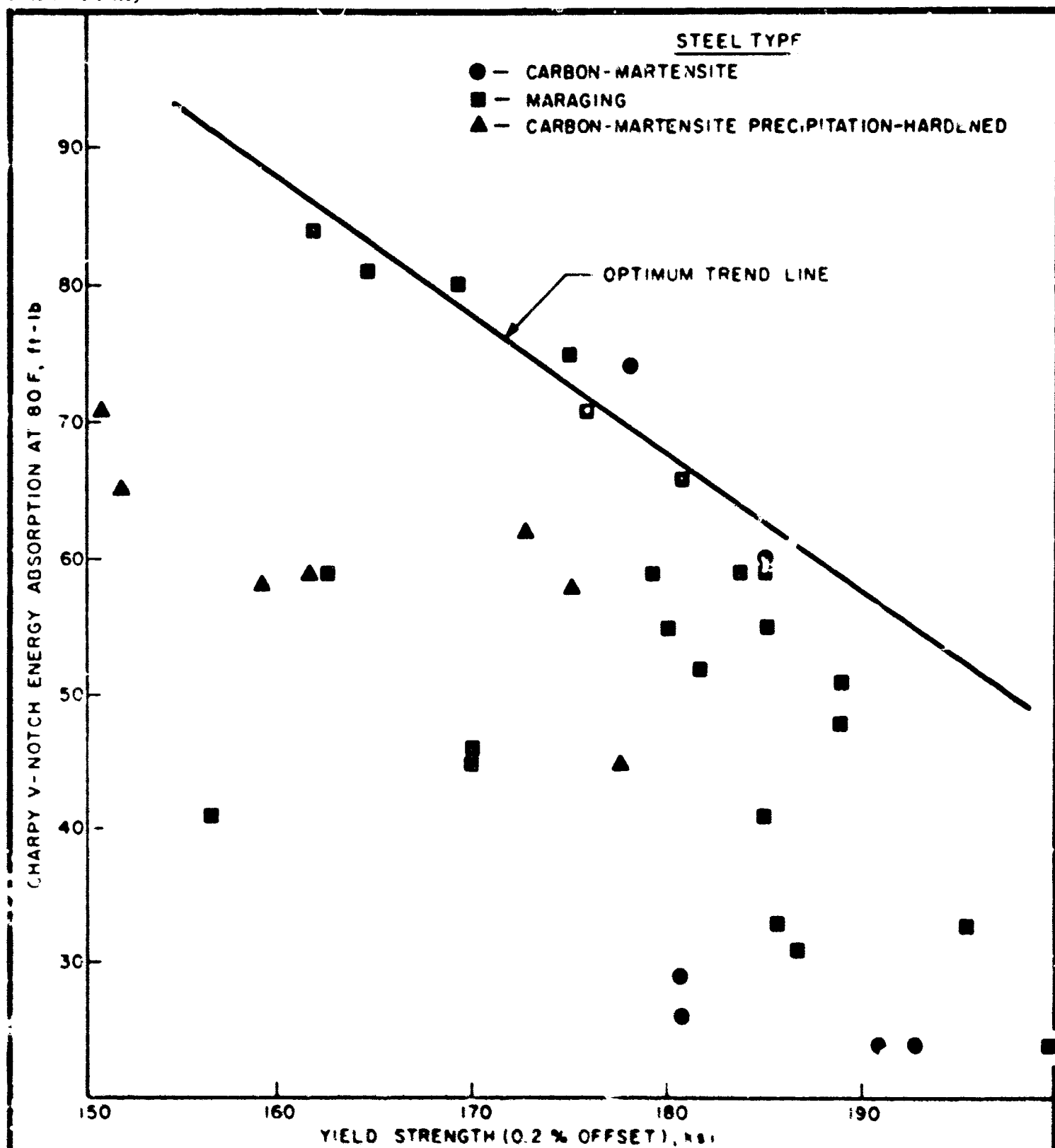
APPLIED RESEARCH

PITTSBURGH, PA.

FIGURE

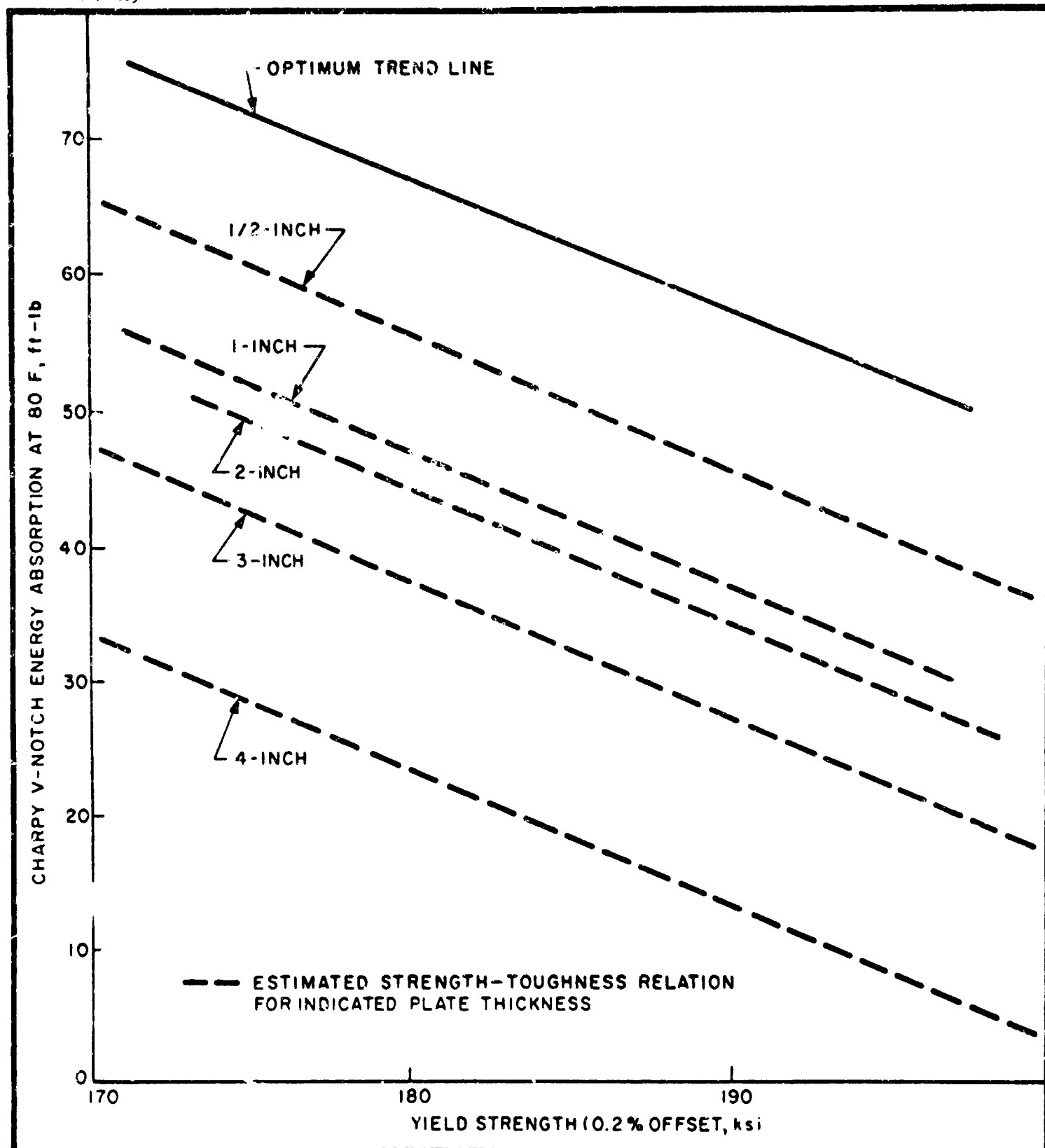
NO.

5



YIELD-STRENGTH-NOTCH-TOUGHNESS RELATION FOR EXPERIMENTAL
HY-180/210 LABORATORY STEELS

DRAWN BY GAZ	CHECKED BY DSO	APPROVED BY JMG	UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA.	FIGURE NO. 6
DRAWING NO. ARL 18-487		PROJECT NO. 40,018-001 (39)		
		DATE 11-24-54		



YIELD STRENGTH AND NOTCH TOUGHNESS OF PLATES FROM
20-TON HEATS OF 12Ni-5Cr-3Mo STEELS

DRAWN BY
G.A.Z.

CHK'D BY
D.S.D.

APPROVED BY
J.H.G.

UNITED STATES STEEL CORPORATION

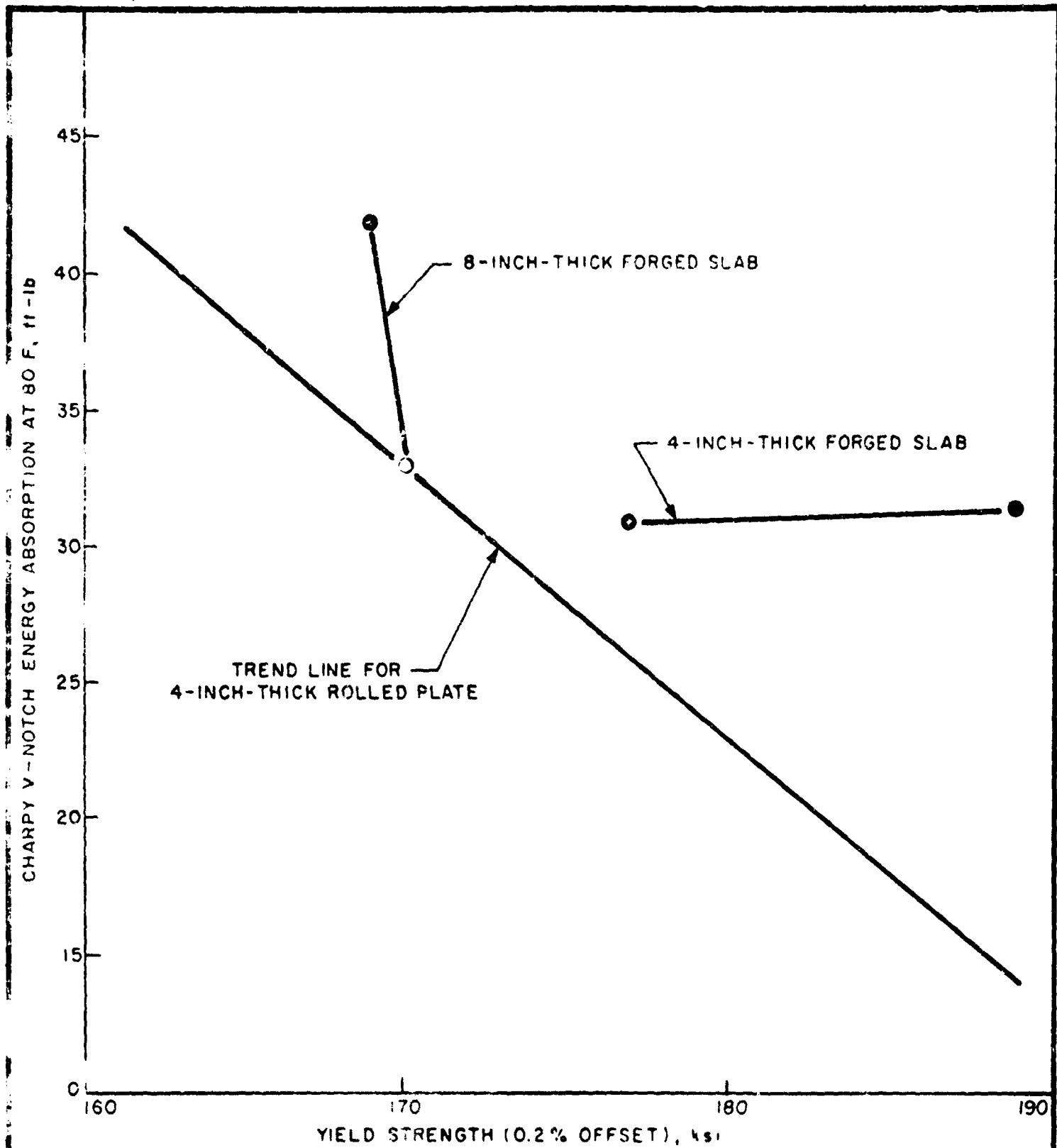
FIGURE

ARL 18-326

DATE
11-24-64

APPLIED RESEARCH
PITTSBURGH, PA.

NO
7



YIELD-STRENGTH-NOTCH-TOUGHNESS RELATION FOR
ROLLED AND FORGED 12Ni-5Cr-3Mo STEEL

DRAWN BY
G.A.Z.

CHK'D BY
D.S.D.

APPROVED BY
J.H.G.

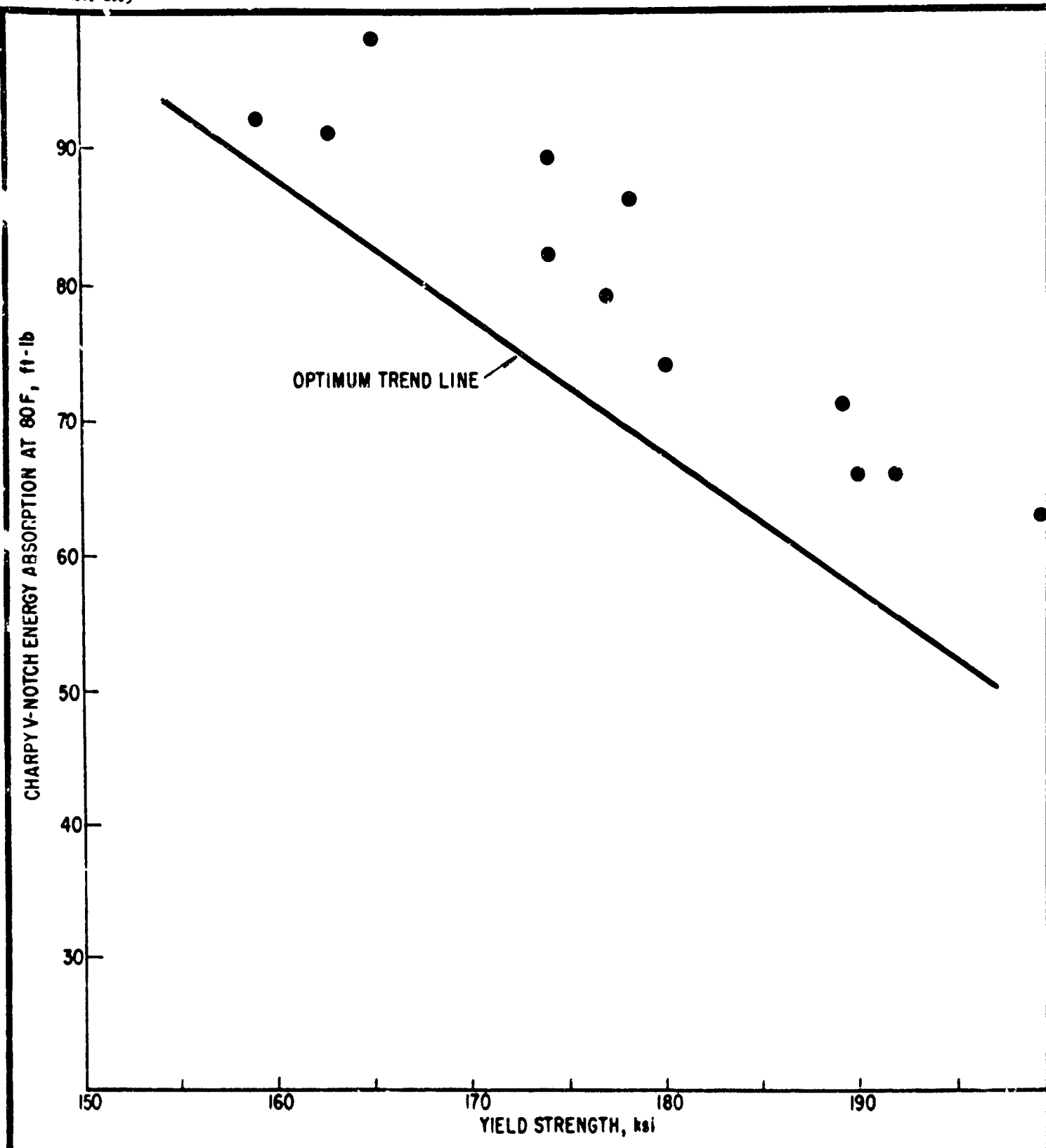
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FIGURE

ARL 18-495

PIT

8



**YIELD-STRENGTH-NOTCH TOUGHNESS RELATION FOR
RAPIDLY HEAT-TREATED 5 Ni-Cr-Mo-V STEEL**

DRAWN BY M.M.	CHK'D BY D.E.O.	APPROVED BY J.H.G.	UNITED STATES STEEL CORPORATION PITTSBURGH, PA.	FIGURE NO 9
ARL 18-489	11/24/64			



X10.



X100.

Figure 10. Stress corrosion cracking in 12Ni-5Cr-3Mo weld metal (bead-on-plate U-bend specimen). Picral nitral and

