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MEMORANDUM REPORT ARLCB-MR-77026

EFFECTS OF QUENCHING TECHNIQUES
UPON GUN STEEL

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May 1977

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
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WATERVLIET, N. Y. 12189

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARLCB-MR-77026	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EFFECTS OF QUENCHING TECHNIQUES UPON GUN STEEL		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) E. H. NICCOLLS		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Benet Weapons Laboratory Watervliet Arsenal, Watervliet, N.Y. 12189 DRDAR-LCB-TL		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS No.3297.06.7236 PRON No.M1-6-A1735-01-M7-M7
11. CONTROLLING OFFICE NAME AND ADDRESS US Army Armament Research and Development Command Large Caliber Weapon System Laboratory Dover, New Jersey 07801		12. REPORT DATE May 1977
		13. NUMBER OF PAGES 20
14. MONITORING AGENCY NAME & ADDRESS(If different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, If different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Quench   Quench Cracking   Hardenability   Critical Diameter

Gun Steel

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The effects of a water, oil and 400°F salt quench upon mechanical properties and microstructure of a 2" thick block of gun steel were studied. The 400°F salt quench was found to be the mildest quenchant. The water and oil quenching effects were compared to the empirical predictions of Grossman with good qualitative agreement.

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INTRODUCTION

The role of metallurgical engineering often seems to lie in exploiting the desirable physical ramifications of a process while evading the negative consequences of the same process. Such is the case of heat treating a medium alloy, high strength steel. Although it is generally recognized that to achieve the desired martensite micro-structure, a fast cooling rate from the austenitizing temperature is required, it is also well known that fast cooling rates may cause severe distortion or even cracking ("quench cracking") in the steel. Therefore, in an attempt to exploit the strength of martensite while evading the disaster of quench cracking, one seeks the optimum cooling (quenching) technique. The experimental work described in this memorandum report was instigated to answer the specific question of whether one could quench a two inch block of gun steel in salt at 400°F and still maintain mechanical properties, and in very general terms, to compare the results of several quenching techniques to those predicted by theory.

REVIEW OF QUENCHING THEORY

The question cited above reflects the dilemma posed by the physics of the martensite transformation. As ex-

-plained in all basic metallurgy tests[1], martensite is not
an equilibrium structure (phase) of steel, but rather is
metastable. If we cool very slowly from the austenitizing
temperature, we eventually reach the equilibrium structure
of pearlite. If our cooling rate is somewhat faster, we
achieve the bainite structure, and if it is very fast, we
obtain the optimum microstructure of martensite. How fast
we cool depends upon two factors; 1) how large the piece
is that we are cooling and 2) the solution, or quenching
medium, that we are using to carry out the cooling process.

For small pieces, relatively little heat is retained
in the piece and even a "mild" quenching medium, such as
oil or air, may shed the heat fast enough to allow the
entire piece to become martensitic. On the other hand,
for larger pieces holding substantial amounts of heat,
a "severe" quenching medium such as cool water or agitated
brine may be required to shed the heat fast enough to
ensure that the piece becomes martensitic. However, under
these conditions of large pieces plunging into a severe
quenching medium, a harmful distortion or cracking may result

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1. See, for example, Barrett, Nix, and Tetelman, The
    Principles of Engineering Materials, Prentice-Hall,
    Inc., 1973, p.p. 306-316.

due to the steep temperature gradient caused by such abrupt cooling. Thus, the dilemma: How do we pick, for a given specimen size, a quenching technique that is the "mildest" possible, yet still able to give us the martensitic micro-structure?

M. A. Grossman, with others, provided a quantitative answer to the dilemma as early as 1939[2,3]. He recognized that the effect of several alloying elements, in particular, carbon, nickel, manganese, chromium, silicon and moly-bednum, was to allow "more time" to reach the martensitic microstructure. That is, the higher alloyed the steel, the slower the cooling rate of the piece could be and still transform to martensite. Conversely, for the same quenching medium, a larger piece of steel could be heat treated to martensite. He described these alloying effects quantitatively in terms of "critical diameters". where the critical diameter was the maximum diameter of a round bar that could achieve (arbitrarily) a 50% marten-site/50% non-martensite microstructure for a given quench-ing medium. The effect of the alloys was to increase the

2. M. Grossman, M. Asimow, and S.F. Urban: Trans. ASM, 1939, vol. 27, p. 125.

3. M. A. Grossman: Trans. TMS-AIME, 1942, vol. 150, p. 227.

critical diameter through "multiplying factors" which varied according to the type and amount of the alloy under consideration. Grossman et al also quantitatively ascertained the relative severity of various quenching media, as given in Table I. When refined, this method provided quite good results, particularly for small pieces and lightly alloyed steels.

PROCEDURE

Three very different quenching techniques were studied - hot salt bath, warm agitated oil, and water. The heat treatments, except for the quenching step, were identical and consisted of austenitizing at 1550°F for one hour, quenching, tempering at 1000°F for one hour, and cooling in agitated oil to room temperature.

In the salt bath quench, the sample was plunged into agitated salt at 400°F until thermal equilibrium was reached. In the oil quench, the sample was immersed in agitated oil at 200°F. For the water quench, the sample was plunged into still water at ambient temperature (approximately 75°F) and manually moved about in the water bath until cool.

The test pieces of 4330V "gun steel", Table II, were heat treated in the form of a 2-1/4" x 5" x 5-1/4" block.

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TABLE I[7]

QUENCH SEVERITY

Agitation of Quenching Medium	Movement of Piece	Severity of Quench ("H")			
		Air	Oil	Water	Brine
None	None	0.02	0.3	1.0	2.2
None	Moderate	-	0.4-0.6	1.5-3.0	-
None	Violent	-	0.6-0.8	3.0-6.0	7.5
Violent or Spray.	-	-	1.0-1.7	6.0-12.0	-

TABLE II

COMPOSITION OF SAMPLES

C	Mn	Ph	Su	Si	Ni	Cr	Mo	Cv	V
.31	.88	.010	.016	.26	1.82	.91	.41	.14	.074

7. From Grossman & Asimow, "Hardening on Quenching", Iron Age 145, 1940, April 25, pp 25-29; May 2, pp 39-45 as shown in Clark & Varney, 2nd Ed., Physical Metallurgy for Engineers, p. 167.

They were then machined to form "2T" fracture toughness specimens (2" x 4.8" x 5.0"). After the fracture toughness testing was completed, standard Charpy and 0.252" tensile specimens were machined out of the broken halves of the fracture toughness specimen. Photomicrographs and grain size measurements were taken of samples from the middle of the fracture toughness specimen.

RESULTS AND DISCUSSION

The results of the mechanical property tests are given in Table III. The three different quenching techniques resulted in modest but readily discernable variations in mechanical properties. The salt quench produced the lowest yield strength, 164 ksi, but the highest -40°F impact toughness (by a slight margin) at 12.3 ft-lbs, while the oil quench resulted in the highest yield strength, 177 ksi, but the lowest -40°F impact toughness, 10.6 ft-lbs. Surprisingly, the water quench, which is the severest of the three, gave intermediate results, although the ductility (as measured by the elongation and the reduction in area) and the fracture toughness were both the highest using this technique. The properties found in the water quenched samples are typical of those for gun steel with a 1550°F

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TABLE III

MECHANICAL PROPERTIES AND MICROSTRUCTURE

	YS[1] (0.1%) ksi	YS[1] (0.2%) ksi	UTS[1] ksi	Hardness (R"C")	EL[1] %	RA[1] %	-40°F[2] Charpy Impact "V" ft-lbs	+80°F[2] Charpy Impact "V" ft-lbs	Fracture[3] Toughness KI_c ksi in.	Grain Size (ASTM)	Structure	YS (.1) / TS
SALT QUENCH	164	167	184	40	15.0	41.3	12.3	22.0	109	9.4	tempered bainite	.89
OIL QUENCH	177	180	193	43	13.0	40.1	10.6	22.4	118	8.8	tempered martensite & bainite	.92
WATER[4] QUENCH	171	174	186	42	16.0	49.0	11.9	25.8	124	9.6	tempered martensite	.92

NOTES:

1. Average of two values
2. Average of three values
3. "Valid" test in accordance with ASTM standard method E399-74
4. Data interpolated from 900°F and 1050°F tempers, water quench

austenitizing temperature and a one hour, 1000°F temper[4], except that the low temperature impact toughness is some four ft-lbs too low.

If the mechanical property results are somewhat ambiguous, the microstructural examination of the three quenching techniques are very definitive. In Figure 1, we see that the microstructure is essentially 100% bainite for the mildest quench, the high temperature salt quench. For the moderate oil quench, we see in Figure 2 that we have a mixture of bainite and martensite. Finally, for the severe water quench, we have virtually 100% martensite as shown in Figure 3. Also evident in Figure 3 is one of the many inclusions found in this rather "dirty" steel, and which undoubtedly explains our uniformly low impact toughness for all three quenches. R.F. Mehl[5] has indicated that inclusions may also reduce the hardenability of a steel.

In Figure 4 are plotted graphs of hardness surveys taken across the broken halves of the fracture toughness sample.

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4.   Peter Dembowski, Unpublished Data, Effect of Tempering Time and Temperature in Gun Steel.

5.   R.F. Mehl, "The Physics of Hardenability", Symposium Hardenability of Alloy Steels, ASM, 1939, p. 1.
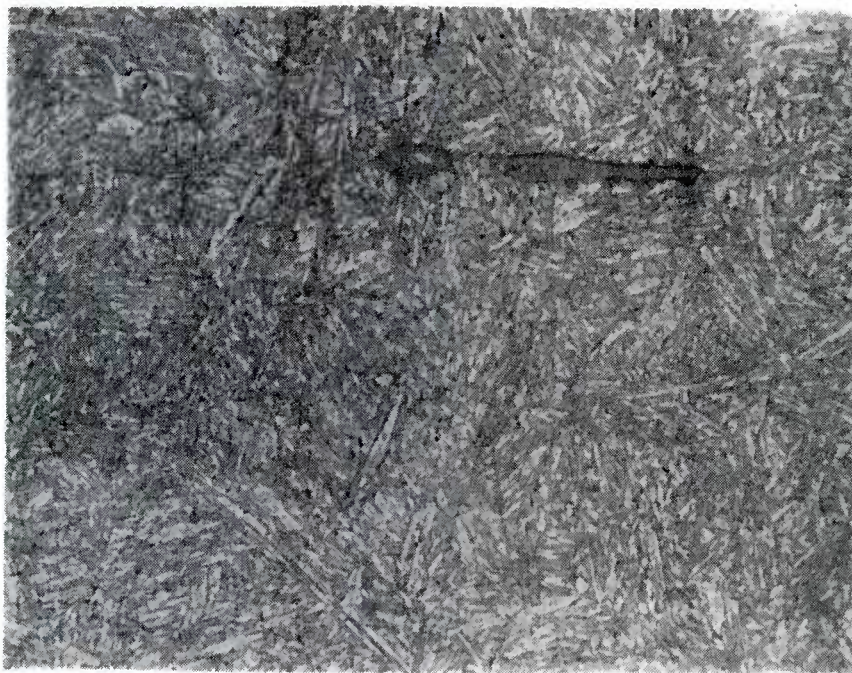
400°F SALT QUENCH - MICROSTRUCTURE
PREDOMINANTLY TEMPERED BAINITE
MAGNIFICATION: 1000X

FIGURE 1

OIL QUENCH - MICROSTRUCTURE: MIXTURE
OF TEMPERED MARTENSITE AND TEMPERED
BAINITE
MAGNIFICATION: 1000X

FIGURE 2

WATER QUENCH - MICROSTRUCTURE: TEMPERED
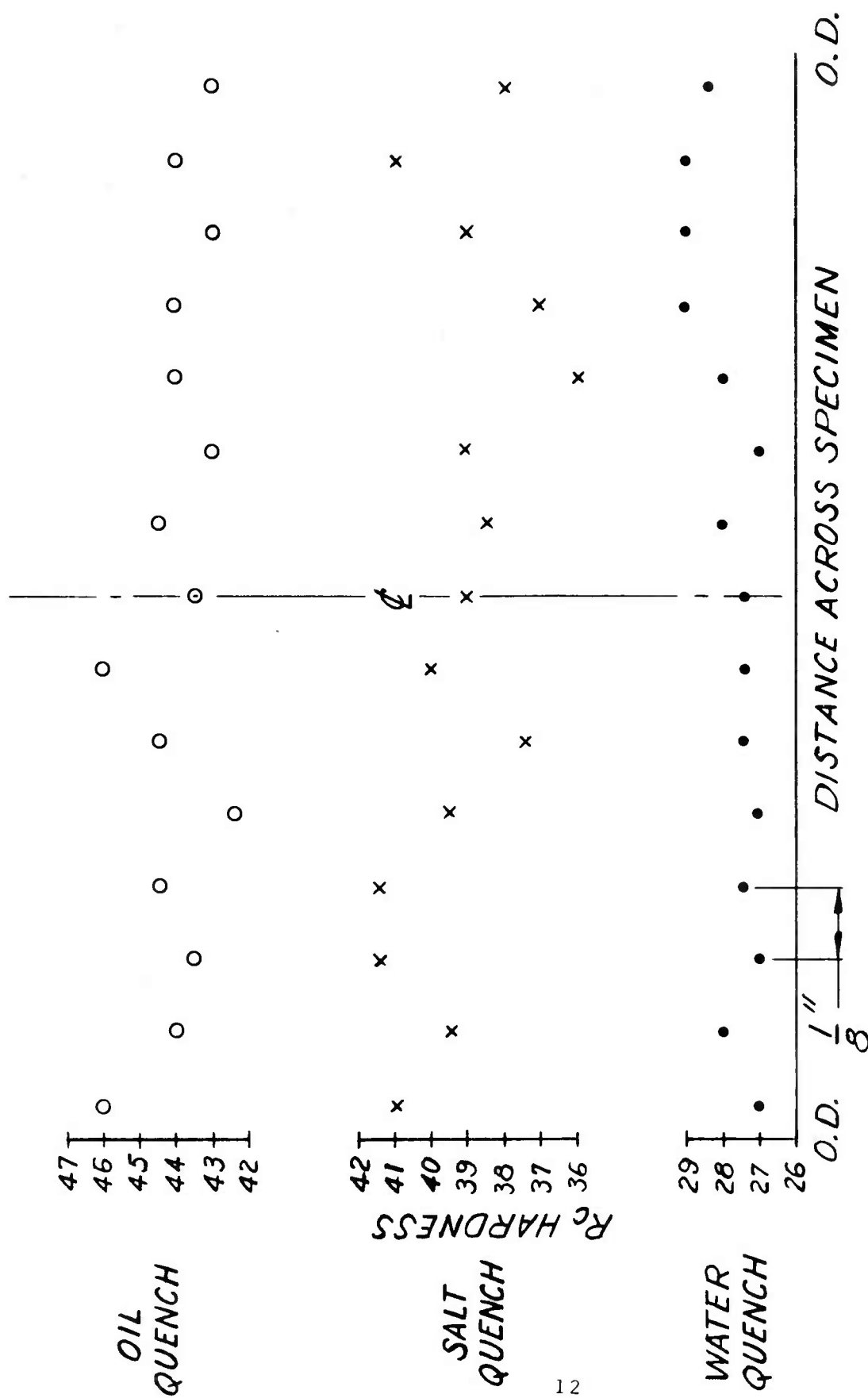MARTENSITE.
MAGNIFICATION: 1000X

FIGURE 3

FIG. 4 REPRESENTATIVE HARDNESS SURVEYS

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Generally, if we have a quenching medium and sample size such that we obtain untempered martensite at the surface and pearlite in the center, we should expect a profound dip in the hardness readings as we reach the center of the sample. In our case, however, our quenching medium and specimen size were such that our cooling rate was so fast that we had all tempered martensite (water quench) or so slow that we had essentially all bainite (salt quench), at least for the section of the samples that remained after the surfaces were ground. For the 200°F oil quench, apparently the cooling rate was well within the range to give a bainite/martensite mixture, and as evidenced by our mechanical properties table, at the 1000°F temper there is only a slight change in hardness as we go from one microstructure to the other. For these reasons we find that the surveys resulted in the flat "curves".

As an exercise to see if the results given above could have been predicted using the Grossman system, the theoretical hardenability of our steel was calculated (see Appendix A). For our chemical composition and grain size, the Grossman method predicted that one could expect to find 99% martensite in the center of a round bar of up to 2.2" for the oil quench (for any larger bar

we would have less martensite and more bainite) and up to 3.3" for the water quench. This is roughly what we found experimentally for our 2.25" thick sample; i.e., essentially all martensite in the center with the water quench, but, with the oil quench, significant amounts of bainite. The amount of bainite that we found with the oil quench was more than predicted, but this is easily explained by noting that Grossman's method was based upon round bars while our actual specimen geometry were relatively wide blocks which would cool more slowly. A calculation for the salt was not even attempted because of the difficulty in assigning qualitatively the severity of this particular quench, and in fact, judgment was also required in the oil quench which is a cause of some error.

Although the geometry of our sample caused the Grossman system to "overestimate" the hardenability of the steel, more often it tends to underestimate highly alloyed steels. C.F. Jatczak[6] explains the discrepancy by pointing out that Grossman implicitly assumed the alloys contribute hardenability to a steel independently of one another, while

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6. C. F. Jatczak, "Hardenability in High Carbon Steels", Metallurgical Transactions, October 1973.

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In fact, they may operate synergistically. The hardenability of our steel was recalculated using the parameters given in Jatczak's article (Appendix B) and the theoretical hardenability did increase moderately.

SUMMARY

We can summarize the results of our experimental work in four statements:

1. The 400°F salt quench was a much milder quench than the 200°F oil quench or the ambient water quench.

2. When quenching a 2-1/4" x 5" x 5-1/4" block of 4330V gun steel, a water quench produced a martensitic microstructure, a 200°F oil quench produced a mixed bainite/martensite structure, and a 400°F salt quench produced a largely bainitic structure.

3. The effects of quenching severity on mechanical properties was not profound under our conditions.

4. When geometry effects were taken into account, traditional empirical theories for predicting depth of hardening were found to be reasonable.

APPENDIX A

HARDENABILITY CALCULATIONS
"Grossman Method"[8]

For 0.31% C and an ASTM grain size of 9, we find from Grossman that the base diameter (D_c) to achieve 50% martensite at the center is about 0.16". Now Mn, Mo, Cr, Si, and Ni all increase this diameter by the relation:

$$D_I = D_c \times F_{Mn} \times F_{Mo} \times F_{Cr} \times F_{Si} \times F_{Ni}$$

Inspecting the graphs of Grossman to find the appropriate multiplying factors for our alloy compositions, we find:

$$D_I = 0.16 \times 3.8 \times 2.2 \times 2.9 \times 1.1 \times 1.7$$

or

$$D_I = 7.3"$$

Thus by this analysis, if we had a quench of inifinite severity, we could quench a bar of 7.3" diameter and get a 50% martensite structure at the core.

Now referring to Table III, we see that the severity of our water quench is roughly 2 (the sample was moved moderately in the water). For the warm oil quench, we take 0.3 as a rough estimate for the H value (warm, but agitated, oil).

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8. Calculations based upon graphs given in Clark & Varney, _Physical Metallurgy for Engineers_, 2nd Edition, pp 167-168, and Guy & Hren, _Elements of Physical Metallurgy_, 3rd Edition, pp 483-486.

It would be misleading to even try to assign a quantitative number for the severity of the 400°F salt quench, but certainly the high temperature produces a much milder quench than the water or oil.

Using the H values for oil and water, we again refer to the plots of Grossman to find that the predicted diameter at which 50% martensite is attained at the center is:

D_c = 6.7 in· for water

D_c = 4.5 in for oil

Utilizing the conversion of 50% martensitic structure to 90% martensitic found in Figure 6 of Jatczak[9], we find that theoretically we can expect to find 90% martensite in sample sizes up to 4.6" round if they are quenched in water and 3.1" round if they are quenched in oil.

Finally, using the same figure we find that theoretically we can expect to find 99% martensite in the center of sample sizes up to 3.3" round if they are quenched in water and 2.2" round if they are quenched in oil.

_____

9.   C.F. Jatczak, "Hardenability in High Carbon Steels
     Metallurgical Transactions, October 1973.

APPENDIX B

HARDENABILITY CALCULATIONS
"Jatczak Method"

C. F. Jatczak[9] utilizes the same form of an empirical relation as Grossman except that he employs a combined Mn-Ni multiplying factor when these elements are present in large amounts. The quantitive amounts of the multiplying factors and the base diameter (D_c) also differ. Thus we have

$$D_I = D_c \times F_{Mn-Ni} \times F_{Si} \times F_{Cr} \times F_{Mo}$$

and using Jatczak's parameters (which are given for <u>90%</u> <u>martensite</u>).

$$D_I = 0.50 \times 5.4 \times 1.18 \times 1.52 \times 1.39$$

or

$$D_I = 6.7"$$

Now we revert to the same quench severity (H) values and Grossman diagrams we used before to obtain:

$D_c = 6.2"$ for water

$D_c = 4.2"$ for oil

These are to be compared to the values of 4.6" and 3.1" calculated earlier for 90% martensite.

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9. C.F.Jatczak, "Hardenability in High Carbon Steels, <u>Metallurgical Transactions</u>, October 1973.

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