WAL TR 401/300
TECHNICAL REPORT

WATERTOWN ARSENAL

LABORATORIES

THE HOT HARDNESS OF TITANIUM AND TITANIUM ALLOYS

BY

F. R. LARSON

O.O. PROJECT: TB4-003, MATERIALS FOR LIGHTWEIGHT CONSTRUCTION
D/A PROJECT: 593-32-003
REPORT NO.: WAL TR 401/300
FILING SUBJECT: TITANIUM

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WATERTOWN ARSENAL
WATERTOWN 72, MASS.

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TITLE

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ABSTRACT

The hot hardness of 27 different heats of titanium and titanium alloys was studied. Tests were conducted on a modified Rockwell machine in an argon atmosphere. Results indicate that low alloy heats lose their hardnesses at a fairly high even rate. On the other hand, high alloy heats hold their hardnesses well up to about 1100°F, and then the hardness drops off very sharply with increasing temperature.

The influence of alloying elements in promoting resistance to softening was evaluated at 900°F. Iron was found to be the most effective with the other elements being arranged in order of decreasing effect, as follows: manganese, molybdenum, aluminum, zirconium, and chromium.

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APPROVED:

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J. F. SULLIVAN
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INTRODUCTION

Of all the mechanical tests at our disposal, hardness is probably the most commonly used for it is both convenient and economical.[1,2] Because of these reasons, along with others, engineers and process metallurgists use this test extensively. Of particular interest in hot fabrication and elevated temperature service is the dependence of hardness upon temperature. Justification of such interest is based upon the correlations that have been established between tensile strength properties and hardness.[3,4] That is, if the temperature dependence of hardness is known for any alloy, it is possible to predict the approximate tensile strength at equivalent temperatures. Furthermore, it is known that when there are sharp changes in the hardness temperature curves there are usually marked changes in the formability or forming forces. It is therefore quite evident that considerable valuable information may be obtained at a minimum of cost. It was for these reasons that a study of the hot hardness of titanium and titanium alloys was undertaken. Furthermore, the tensile, creep, and rupture properties of titanium at elevated temperatures have been summarized by Battelle Memorial Institute,[5] but no hot hardness data have been yet reported.

The hot hardness testing was done at Mallory-Sharon Titanium Corporation under Contract Numbers DA-33-008-ORD-887 and DA-33-008-ORD-196 on samples supplied by this laboratory. The results of these hot hardness tests were reported in the form of separate letter reports, one for each alloy tested. Furthermore, no attempt was made to analyze the data. It is therefore the purpose of this report to compile all of the data in one document and, of greater importance, to interpret the results.

MATERIALS

Fifteen commercially available titanium and titanium alloys selected for the experiment were chosen as representative of production composition. Twelve experimental compositions were included particularly because of reported interest in them for one reason or another. The chemical analysis of these materials is listed in Table I. The microstructures and true stress-true strain properties for Lots 1 through 12 and the impact properties of Lots 1 through 4, 6, 9, 10, and 12 have been previously reported.[6,7] The tensile properties of the remainder of the materials are listed in Table II. All materials were annealed for one hour at 1300°F in argon prior to testing.

TEST PROCEDURE

The details of the test apparatus employed by the contractor are presented in Figures 1 and 2. Equipment consisted of a modified Rockwell hardness tester. The modifications were mainly a furnace mounted on an elevating anvil, in which a protective atmosphere, in this case argon, could be provided, and an extension on the indenter so that it could be located above the specimen in the furnace. In addition, there was also a provision for locating the specimen from outside of the furnace so that several tests could be run on the same sample without opening the furnace.

The hardness was measured on the Rockwell "A" scale at room temperature, 300°F, and then in increments of 100°F until the readings went off scale or 1300°F whichever was reached first. Time of load application and time at temperature were not reported and is not considered important if equilibrium was reached as was required in the contract. Furthermore, all specimens were annealed at or above the highest testing temperature. Four specimens that were checked for room temperature hardness after a run had been made, revealed that no change had occurred, indicating no influence of contamination or tempering. The results of this testing are portrayed in Figures 3 through 29.

DISCUSSION OF RESULTS

Examination of the above curves, plotted on the conventional log of hardness versus linear temperature basis, will reveal that there are considerable differences in the behavior patterns for the various alloys. The different compositions are softened in a variety of ways. The important observation to make from a fabrication standpoint is that the main drop in hardness, especially for the more heat-resistant alloys, occurred at approximately 1200°F. Furthermore, when 1300°F was reached many alloys were so soft that it was impossible to obtain hardness readings.

Apparently this sharp change in slope is the equi-cohesive break[8] corresponding to the recrystallization temperature and also the maximum useful temperature for medium and long-time service applications for these alloys. There is, of course, another possibility based on the fact that the hot strength of the hexagonal close-packed alpha phase exceeds by a considerable margin that of body-centered cubic phase (see Reference 8). This possibility exists in the alloys that contain beta-stabilizing elements in sufficient quantity to lower the alpha to alpha plus beta phase boundary into the temperature range in which the hardness tests were conducted so that the softer beta sharply reduced the hot hardness of the mixed alpha plus beta structure.

Another important point to study is the relative resistance to softening of the various compositions, or more ideally, to discover the separate effects of the various alloy elements. Finlay and Snyder,[9] while working on alpha titanium interstitial alloys containing carbon, nitrogen, and oxygen, reported a linear relationship between the tensile strength and the equivalent nitrogen (atomic percent). In their investigation, it was established that nitrogen was the most powerful strengthener, and the other interstitials were converted to equivalent nitrogen by a ratio, such as oxygen being only 0.82 percent as effective as nitrogen. This approach was utilized to evaluate the influence of alloying elements upon the hot hardness of these alloys. First, 900°F was chosen as the temperature for study mainly because it is the maximum temperature just below the lowest known for these alloy's alpha to beta reaction. For the establishment of the factors, main consideration was given to those elements that appeared to produce the most effect, mainly the metallic elements. Oxygen, nitrogen, and carbon were not considered because their influence was small, and the atomic percentages when compared with the metallic elements were also small. It became immediately obvious that iron produced the most powerful effect, and, therefore, by comparing compositions at equivalent hot hardness levels the influence of the remaining alloying elements was determined in terms of iron, with the following equation covering the conditions for this experiment as illustrated by Figure 30:

$$\text{Equivalent }\%^{*}\text{Fe} = \%\text{Fe} + \frac{\%\text{Mn}}{3.38} + \frac{\%\text{Mo}}{5.10} + \frac{\%\text{Al}}{6.40} + \frac{\%\text{Zr}}{7.47} + \frac{\%\text{Cr}}{13.66}$$

The elements in this equation are arranged in order of decreasing effect, with iron equal to one. Manganese was found to be approximately 1/3.4, molybdenum 1/5.1, aluminum 1/6.4, zirconium 1/7.4, and chromium 1/13.6 as effective as the iron.

CONCLUSIONS

The results of this hot hardness program reveal that titanium and titanium alloys exhibit similar behavior patterns to other metals, as follows:

1. Low alloy compositions lose their hardnesses fairly evenly with increasing temperatures with no sharp breaks occurring in the hardness versus temperature curves.

2. High alloy compositions hold their hardnesses with increasing temperature fairly well depending upon the alloy; and finally when the temperature is sufficiently high (1000 to 1200°F) the hardness drops off very sharply at or near a temperature that appears to be the equi-cohesive temperature.

3. The effect of alloying elements upon the hot hardness at 900°F was studied, and it was found that iron exhibited the most potent effect. The other alloying elements were rated in terms of equivalent iron, and the following equation expresses the results:

$$\text{Equivalent }\%\text{Fe} = \%\text{Fe} + \frac{\%\text{Mn}}{3.38} + \frac{\%\text{Mo}}{5.10} + \frac{\%\text{Al}}{6.40} + \frac{\%\text{Zr}}{7.47} + \frac{\%\text{Cr}}{13.66}$$

* % refers to atomic percent.

ACKNOWLEDGMENT

The author would like to express his thanks to Mr. S. V. Arnold* who arranged the hot hardness contract, to Mr. J. Nunes** who helped in analyzing the data, and to Mr. D. C. Buffum* who supplied the zirconium alloys.

* *Physical Metallurgist, Watertown Arsenal Laboratories*

** *Physical Science Aide, Watertown Arsenal Laboratories*

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3. BENS, F. P., "Hardness Testing of Metals and Alloys at Elevated Temperatures," *Trans ASM* 38 (1947) 505.

4. GAROFALO, F., MALENOCK, P. R. and SMITH, G. V., "Hardness of Steels at Elevated Temperatures," *Trans ASM* 45 (1953) 377.

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6. KULA, E. B., and LARSON, F. R. "True Stress-True Strain Properties of Titanium and Titanium Alloys," Watertown Arsenal Laboratories Report No. WAL 401/241, 2 Sept. 1955.

7. KULA, F. B. and LARSON, F. R., "Effect of Vacuum Annealing on the Impact Properties of Titanium and Titanium Alloys," Watertown Arsenal Laboratories Report No. WAL 401/259, 19 April 1956.

8. LUNSFORD, J. and GRANT, N. J., "Relative High Temperature Properties of the Hexagonal Close-Packed and Body-Centered Cubic Structures in Iodide-Titanium," *Trans ASM* 49 (1957) 328.

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TABLE I

CHEMICAL ANALYSIS

Mark	Grade	Heat No.	O	H	N	C	Fe	Al	Cr	Mn	Mo	Sn	Zr	Test Specimen No.
RH1G4	A55	T5-3328	.119	.0052	.034	.02	.24	-	-	-	-	-	-	1
TH1F2	A55	T5-3303	.096	.0030	.022	.01	.26	-	-	-	-	-	-	2
SXA7	RS55	U*	.164	.013	.036	.09	.10	-	-	-	-	-	-	3
TH1G2	Ti100A	-	.127	.0090	.054	.05	.48	-	-	-	-	-	-	4
SXE4	4Mn	R1A-506	.203	.0068	.034	.06	.15	-	-	3.36	-	-	-	5
RH1G5	C110M	A-3278	.137	.0062	.040	.03	.26	-	-	6.44	-	-	-	6
RXG5	C110M	B-3275	.156	.0079	.024	.03	.19	-	-	6.18	-	-	-	7
RJ1A2	C110M	AW3477B	.112	.009	.024	.032	.09	-	-	6.86	-	-	-	8
RH1B2	C130AM	B3198	.135	.0062	.030	.06	.16	3.34	-	3.40	-	-	-	9
TH1J2	Ti150A	-	.437	.025	.046	.014	.84	-	1.27	-	-	-	-	10
TXF2	Ti150A	L-903	.335	.012	.058	.04	1.5	-	2.61	-	-	-	-	11
TH1L5	Ti150B	L-1038	.163	.016	.054	.05	4.6	-	4.66	-	4.8	-	-	12
RH1C1	A55	-	-	-	-	.10	-	-	-	-	-	-	-	13
RH1E2	C110M	-	-	-	-	.13	-	-	-	7.9	-	-	-	14
RH101	RC70	-	-	-	-	.09	-	-	-	-	-	-	-	15
RS14	*	-	-	-	.034	.115	1.52	-	3.85	.088	-	-	-	16
R26	*	-	-	-	.045	.03	.27	3.37	-	-	-	1.53	-	17
R110	*	-	-	-	.064	.09	-	-	3.93	6.77	4.26	-	-	18
A25	*	-	.125	.008	.036	.04	.06	-	3.77	-	2.48	-	-	19
K100	*	-	.15	.023	.040	Tr	5.35	-	11.84	-	-	-	-	20
TiZ1	*	-	.104	.0034	.014	.02	.08	-	-	-	-	-	>.01	21
TiZ2	*	-	.115	.0034	.016	.025	.09	-	-	-	-	-	5.22	22
TiZ3	*	-	.111	.0033	.015	.025	.11	-	-	-	-	-	9.45	23
TiZ4	*	-	.100	.0042	.008	.025	.09	-	-	-	-	-	13.8	24
TiZ5	*	-	.104	.0065	.010	.03	.10	-	-	-	-	-	24.9	25
TiZ6	*	-	.103	.0054	.013	.03	.10	-	-	-	-	-	26.3	26
TiZ7	*	-	.104	.0031	.016	.04	.11	-	-	-	-	-	31.5	27

*Denotes experimental alloy.

TABLE II

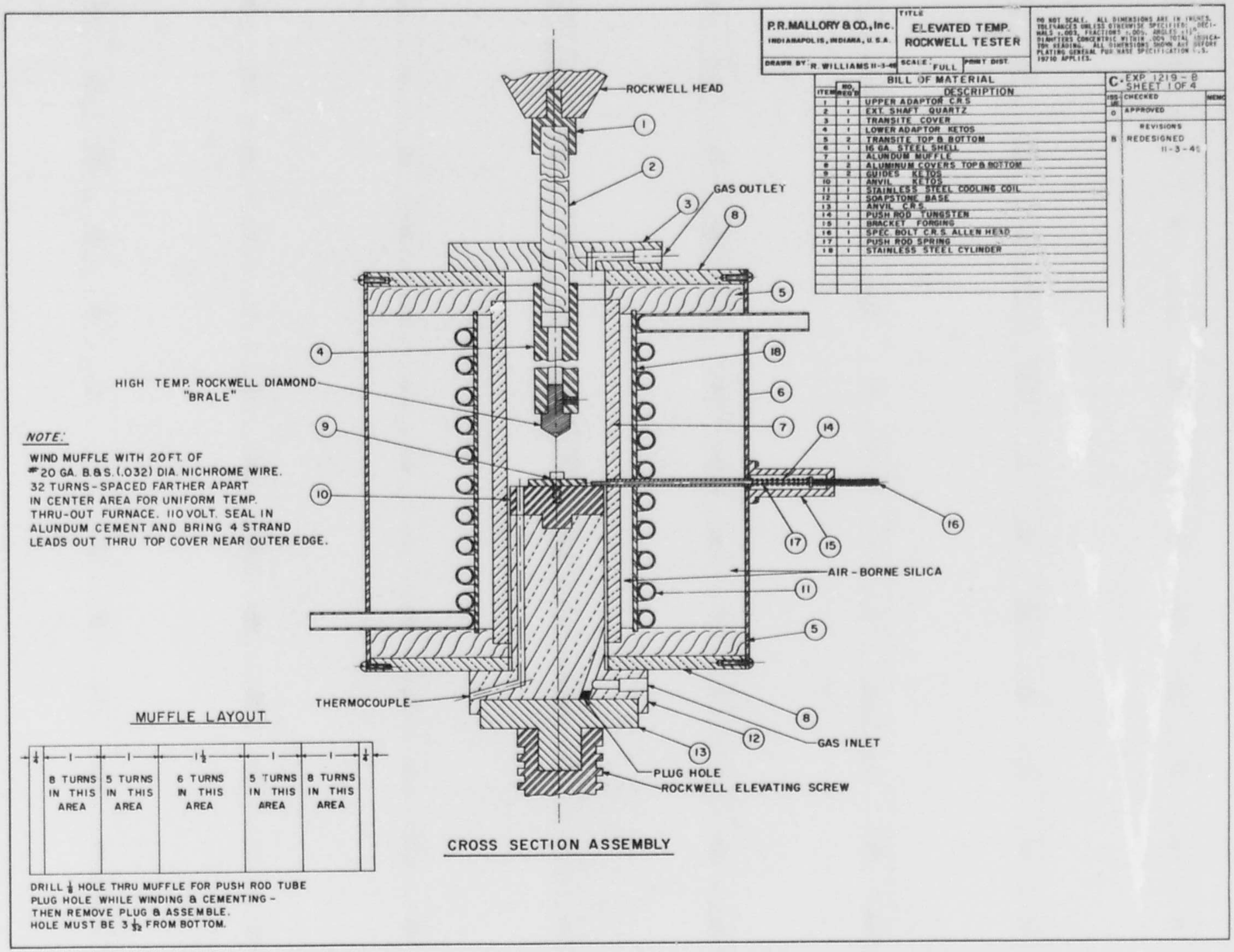
MECHANICAL PROPERTIES
(Room Temperature)

EXPERIMENTAL ALLOYS						
Mark	Specimen Direction	Yield Strength .01%	Yield Strength .1%	Tensile Strength	% Elong.	% R.A.
RS-14	L	75,800	89,000	114,600	19.3	34.5
	T	87,000	97,000	118,800	15.0	25.1
A-25	L	92,000	99,000	106,400	25.0	68.3
	T	97,000	101,000	108,000	24.3	67.3
R22	L	88,000	96,000	119,000	20.7	51.7
	T	83,000	99,000	124,500	19.3	45.3
R26	L	68,500	76,000	89,000	19.3	52.1
	T	51,500	59,500	76,000	22.9	49.8
R110	L	134,100	139,000	139,500	16.4	48.0
	T	136,000	141,000	141,500	20.7	51.4
K100	L	141,000	149,500	155,000	12.1	43.2
	T	141,000	-	144,250	*	*

COMMERCIAL ALLOYS						
	Grade					
RH1-C1	A55	68,000	**	86,500	27.0	**
RH1-D1	RC70	85,400	**	98,600	24.3	45.2
RH1-E2	C110M	126,900	**	132,800	23.2	**

*Broke on gage mark.

**Not reported.



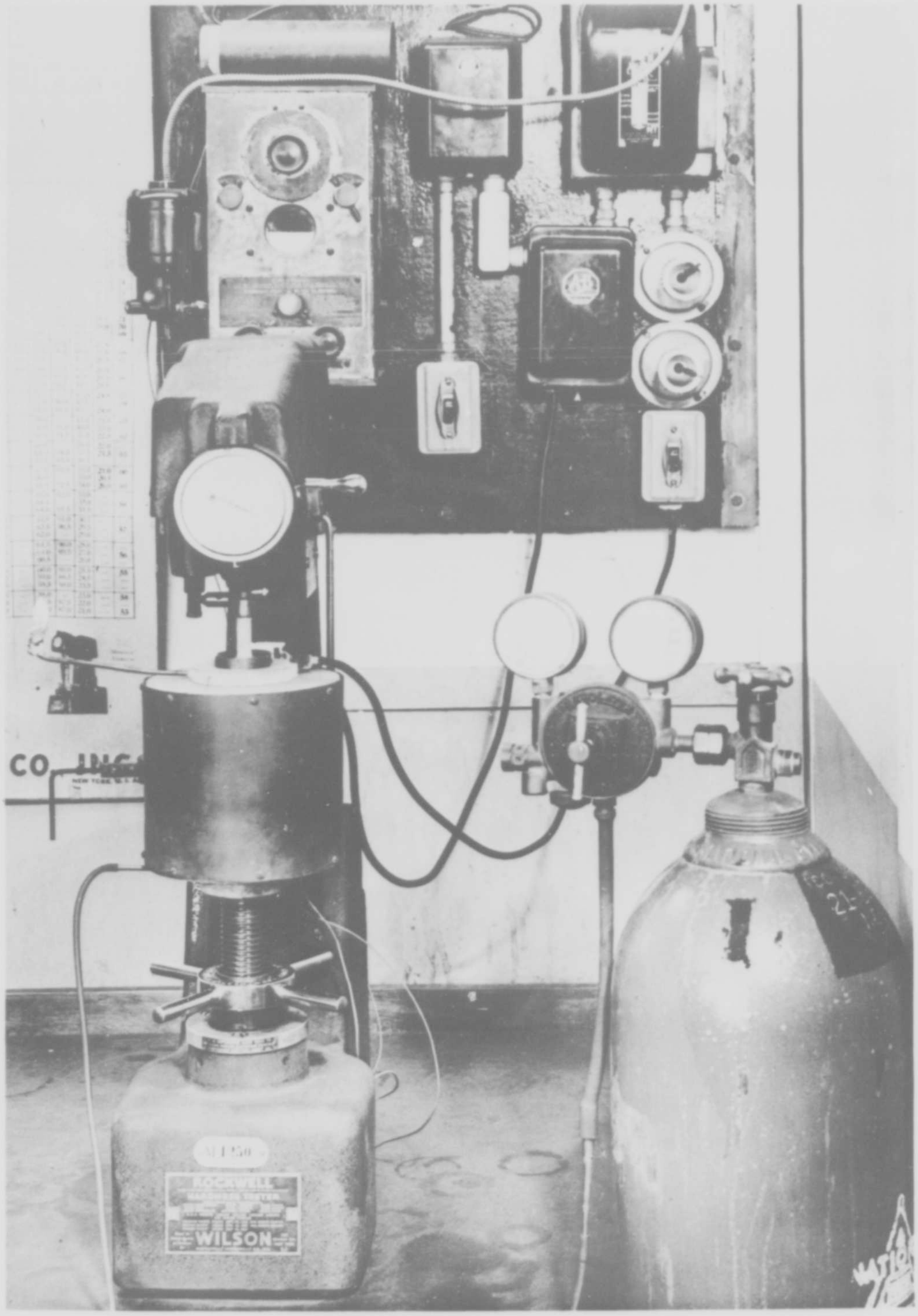
BILL OF MATERIAL

ITEM	NO. REQ'D	DESCRIPTION
1	1	UPPER ADAPTOR C.R.S.
2	1	EXT. SHAFT QUARTZ
3	1	TRANSITE COVER
4	1	LOWER ADAPTOR KETOS
5	2	TRANSITE TOP & BOTTOM
6	1	16 GA. STEEL SHELL
7	1	ALUNDUM MUFFLE
8	2	ALUMINUM COVERS TOP & BOTTOM
9	2	GUIDES KETOS
10	1	ANVIL KETOS
11	1	STAINLESS STEEL COOLING COIL
12	1	SOAPSTONE BASE
13	1	ANVIL C.R.S.
14	1	PUSH ROD TUNGSTEN
15	1	BRACKET FORGING
16	1	SPEC. BOLT C.R.S. ALLEN HEAD
17	1	PUSH ROD SPRING
18	1	STAINLESS STEEL CYLINDER

LINE DRAWING OF HOT HARDNESS APPARATUS

Wtn. 639-16, 327

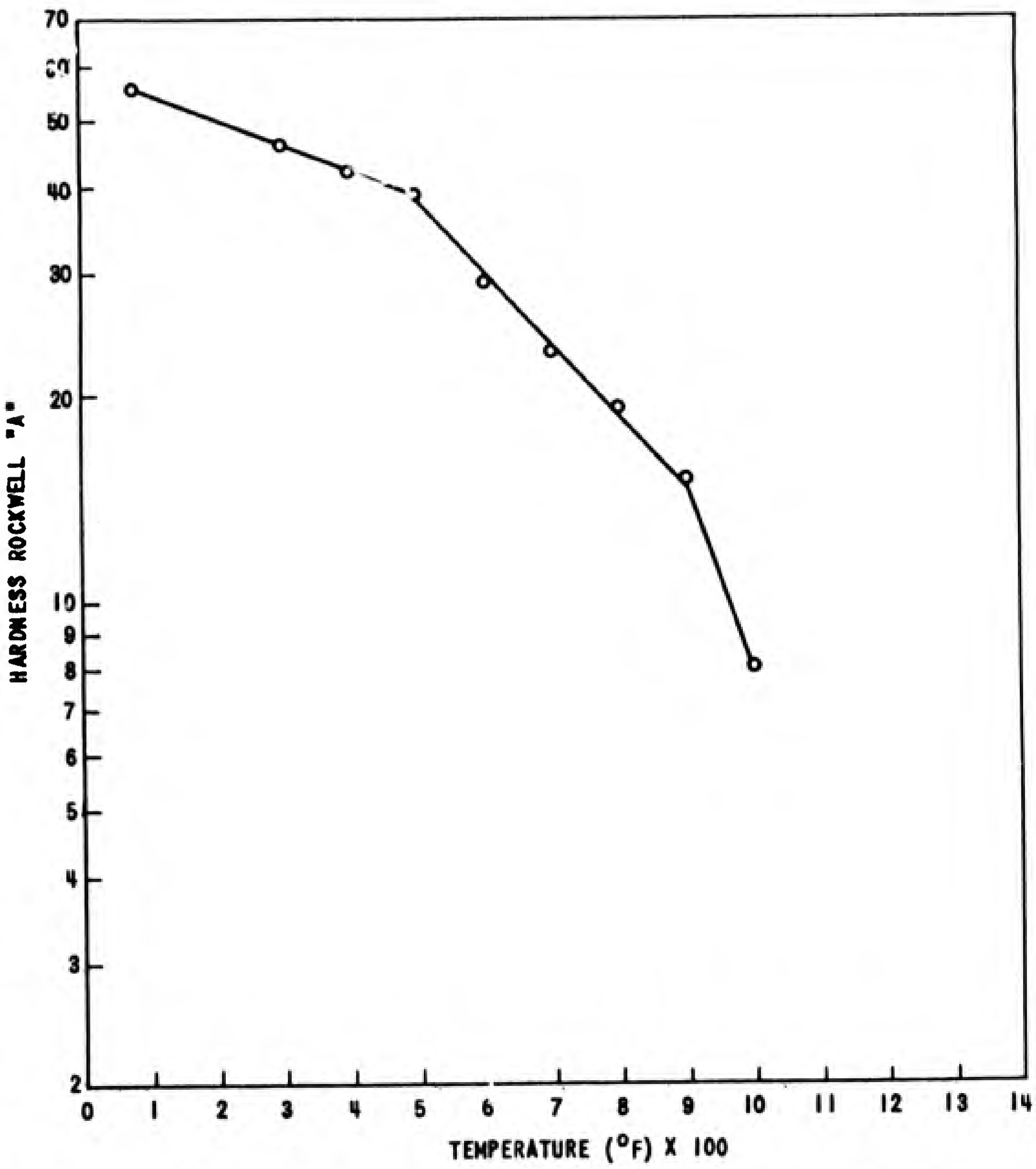
FIGURE I



PHOTOGRAPH OF HOT HARDNESS SET-UP

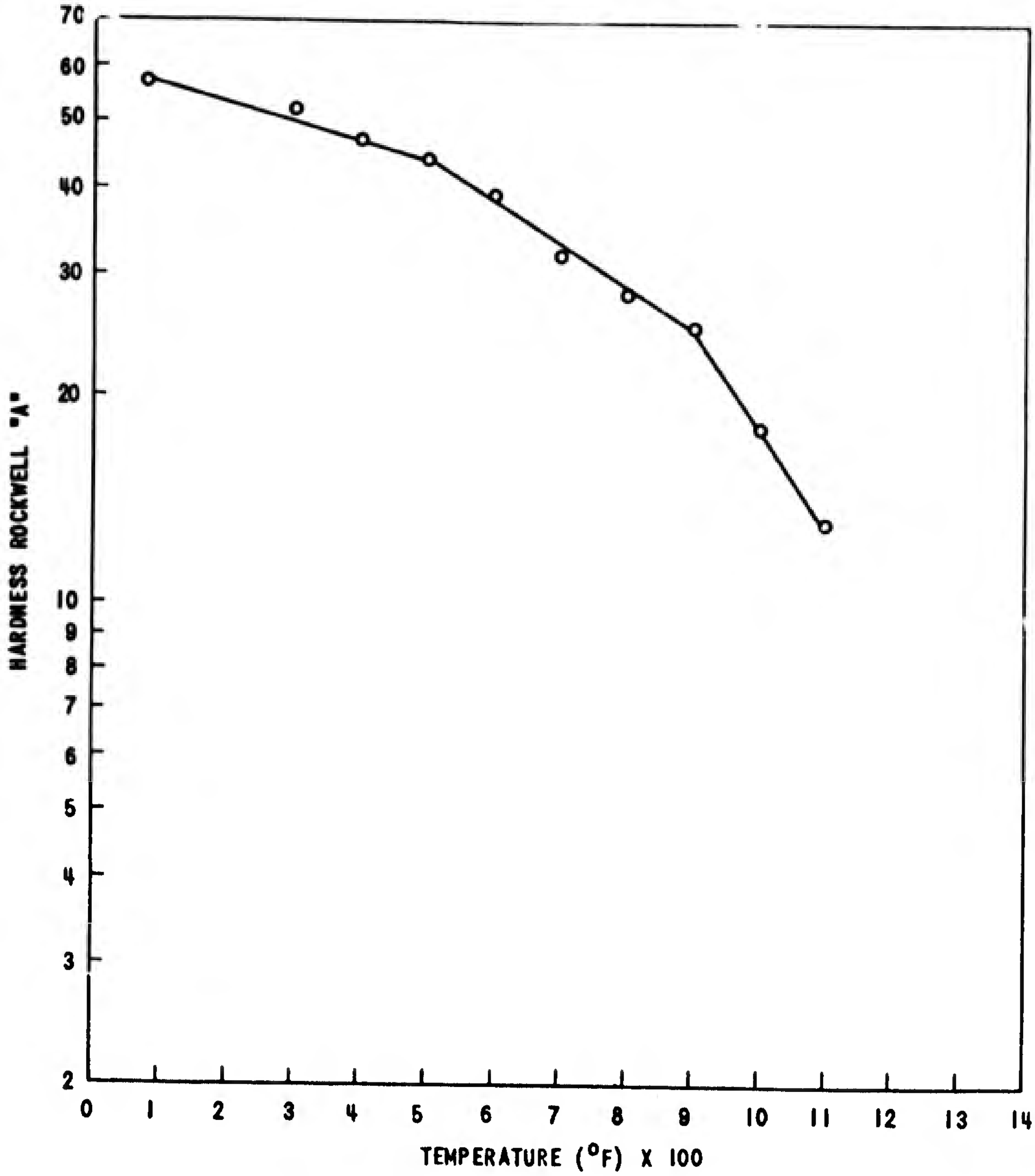
Wtn. 639-16, 328

FIGURE 2



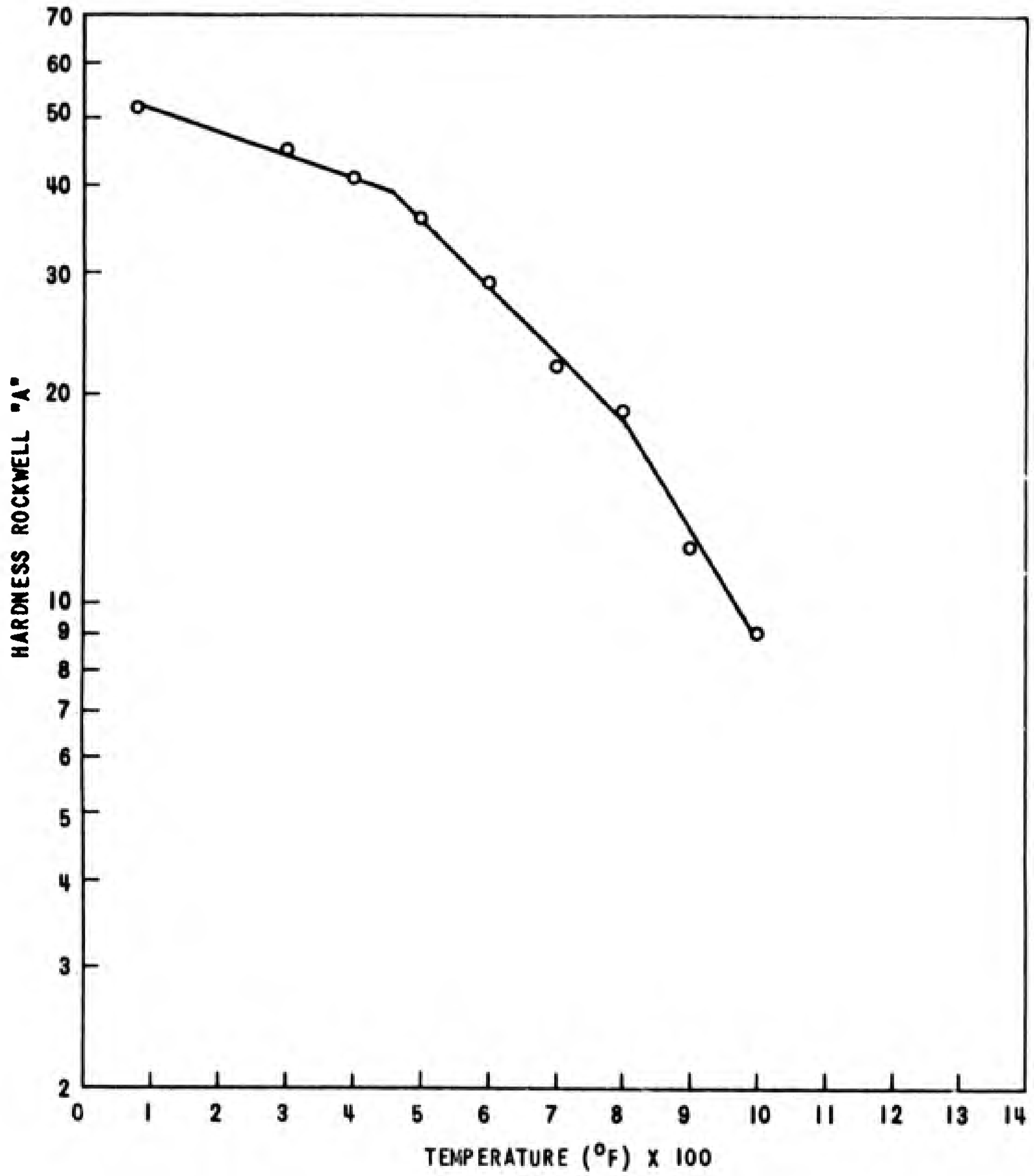
EFFECT OF TEMPERATURE ON THE HARDNESS OF A55 (RH1G4)

FIGURE 3



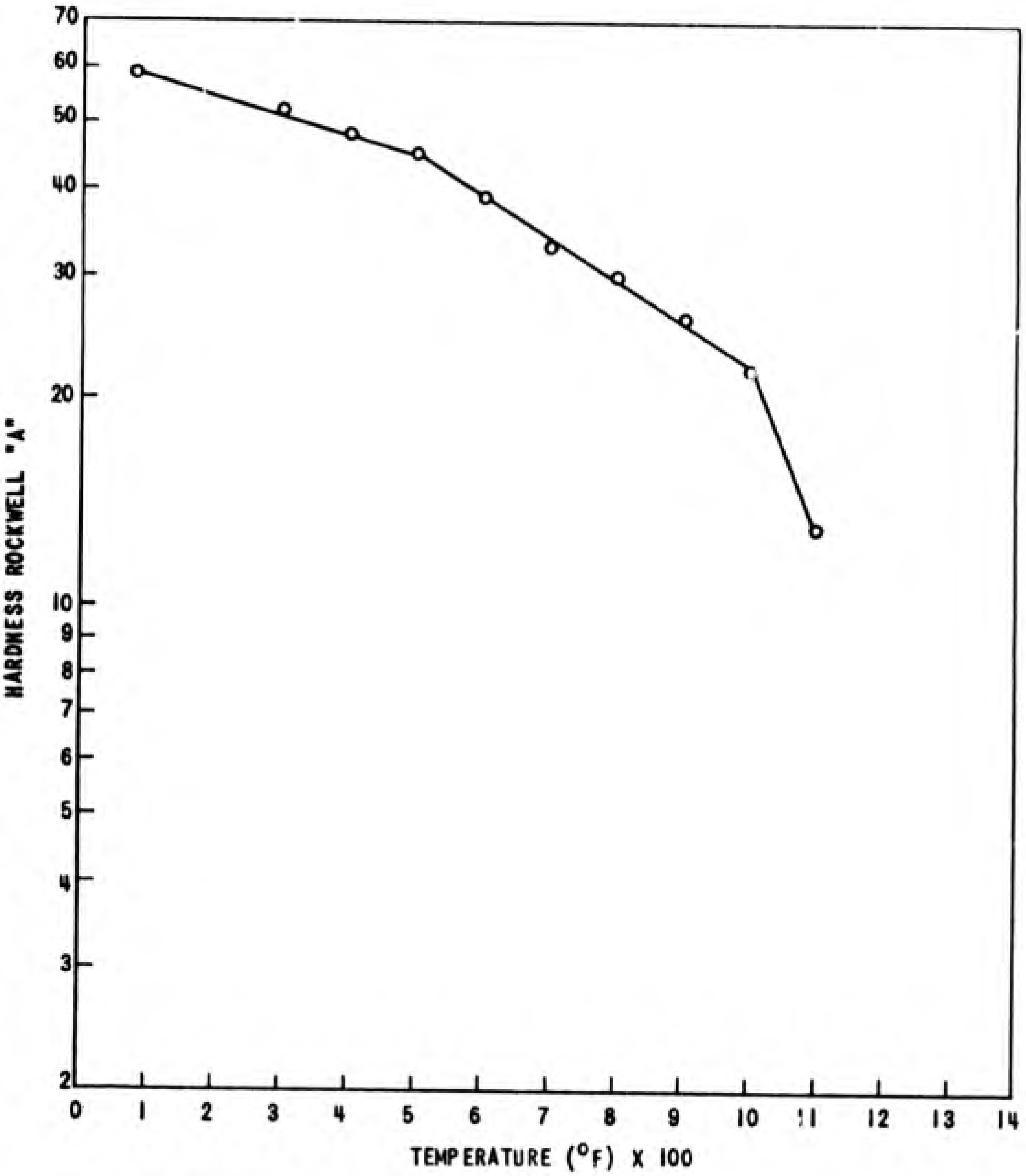
EFFECT OF TEMPERATURE ON THE HARDNESS OF A55 (THIF2)

FIGURE 4



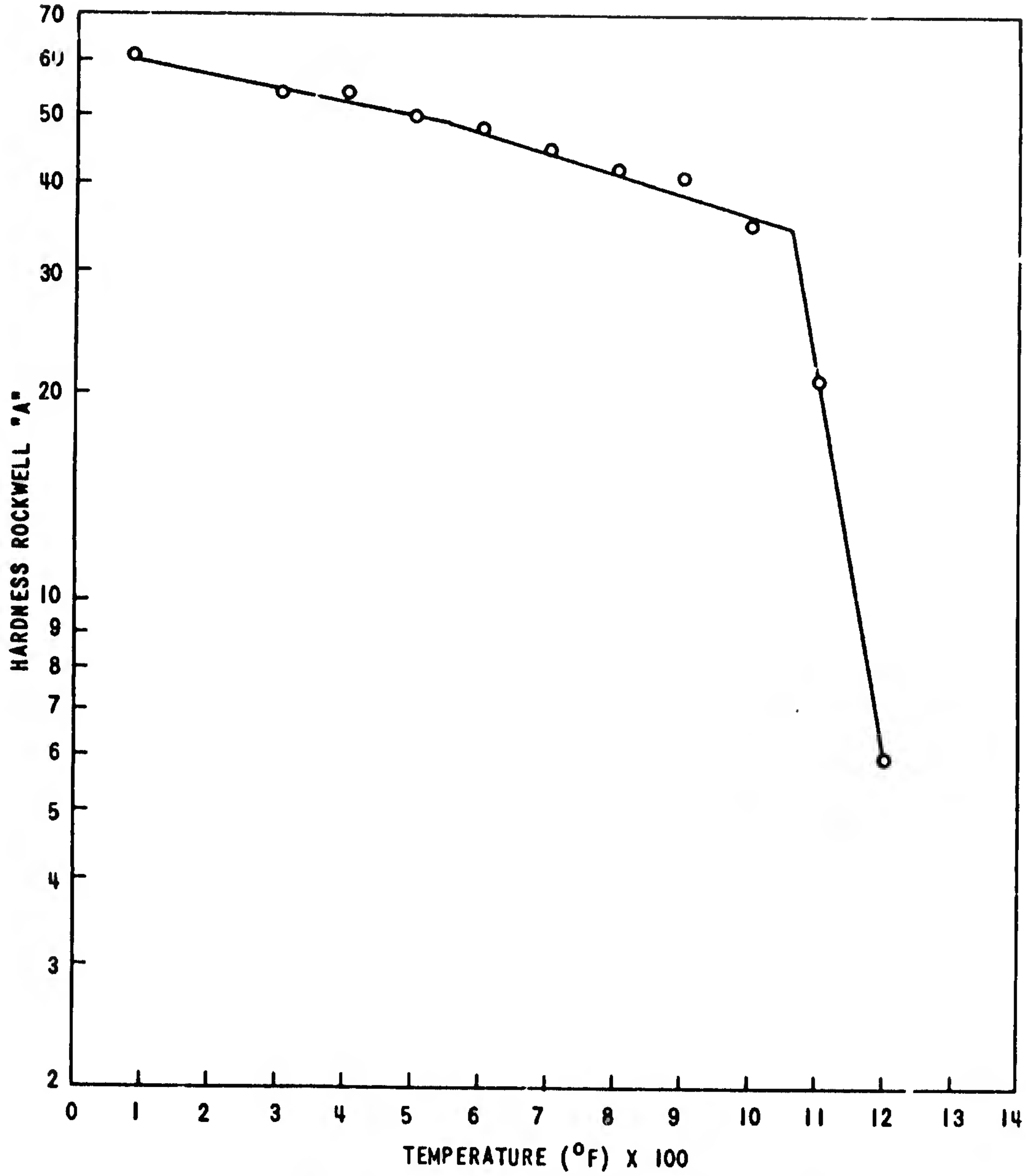
EFFECT OF TEMPERATURE ON THE HARDNESS OF RS55(SXA7)

FIGURE 5



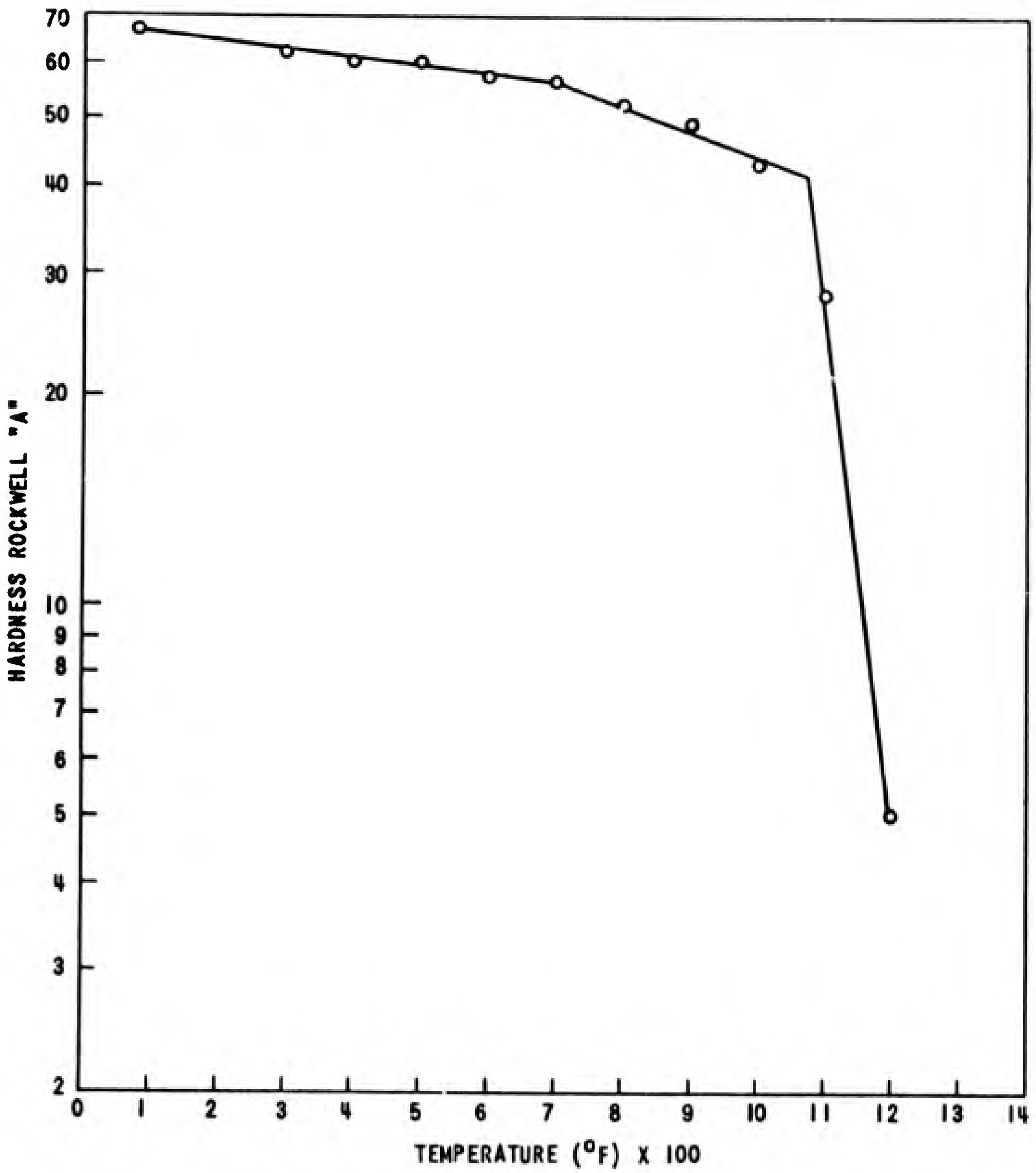
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti100A (THIG2)

FIGURE 6



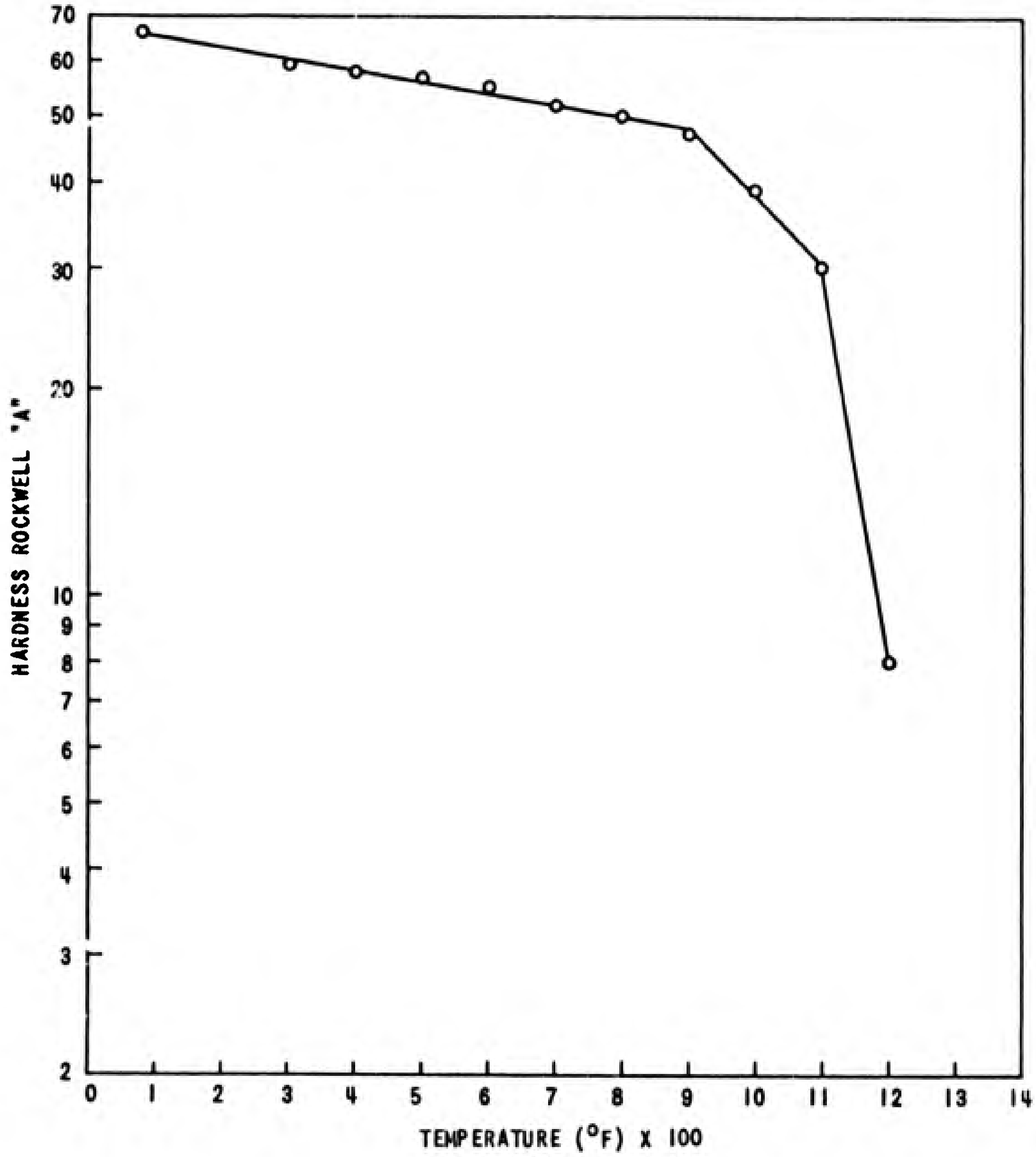
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-4Mn (SXE4)

FIGURE 7



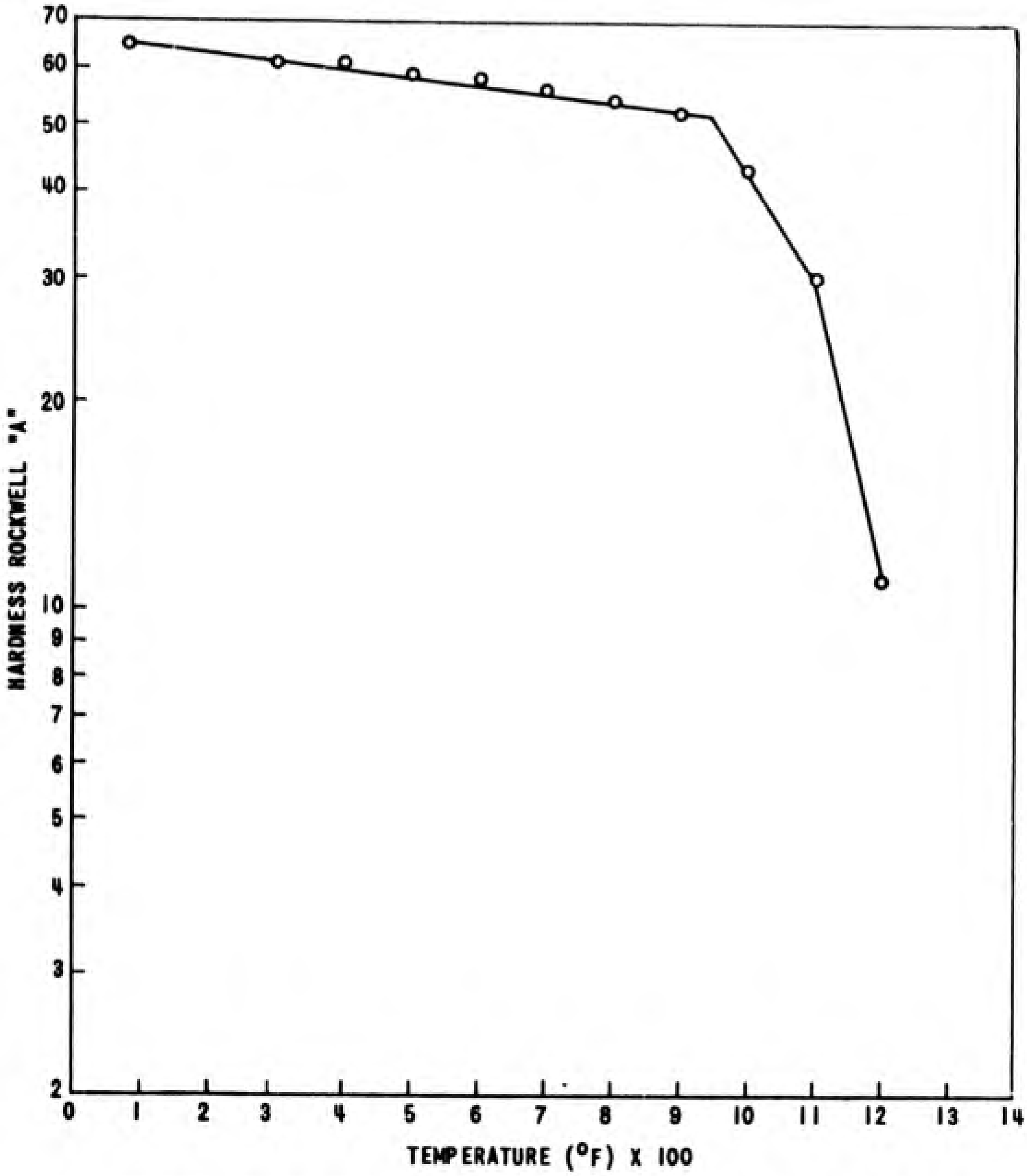
EFFECT OF TEMPERATURE ON THE HARDNESS OF C110M (RH165)

FIGURE 8



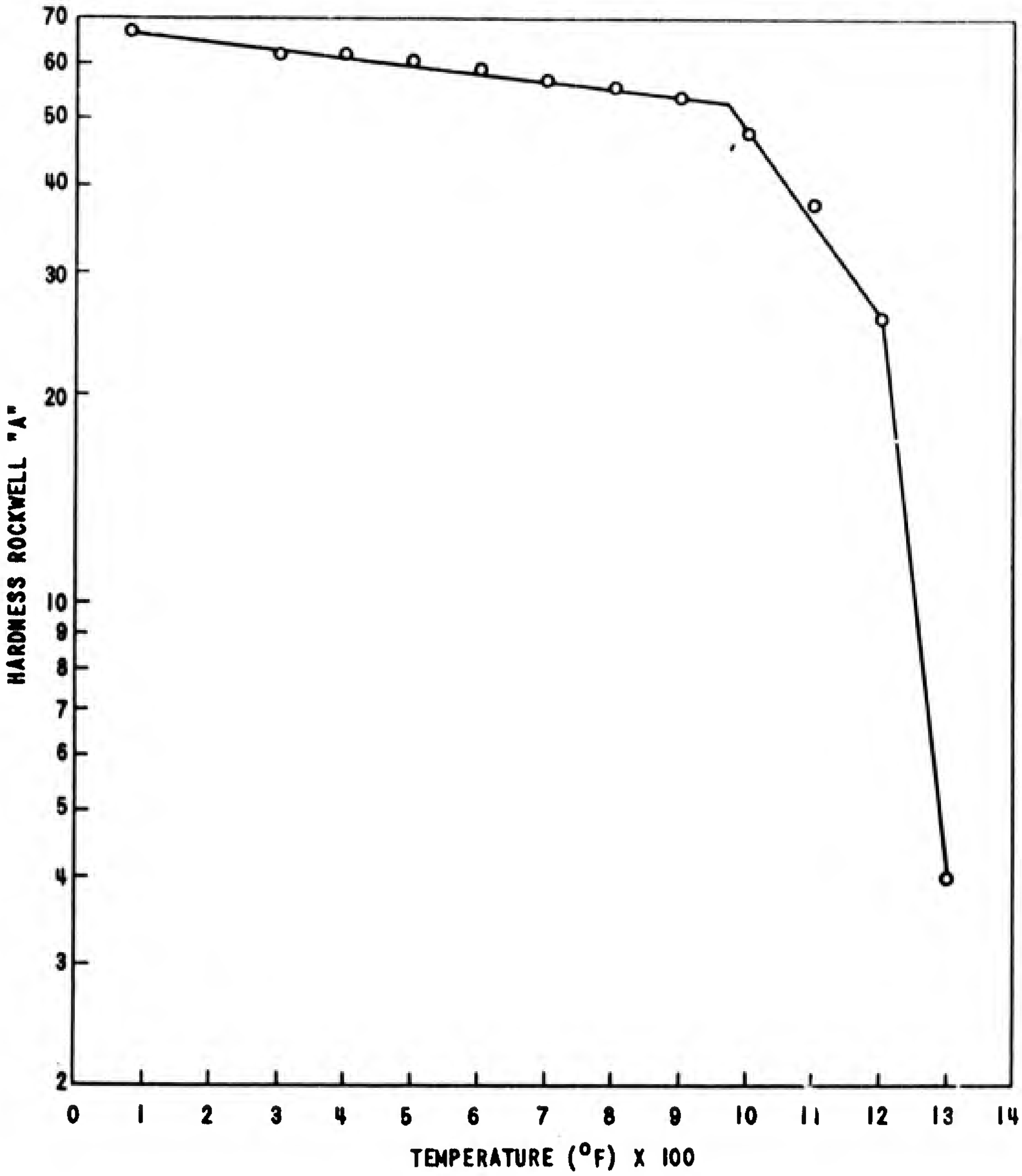
EFFECT OF TEMPERATURE ON THE HARDNESS OF C110M (RXG5)

FIGURE 9



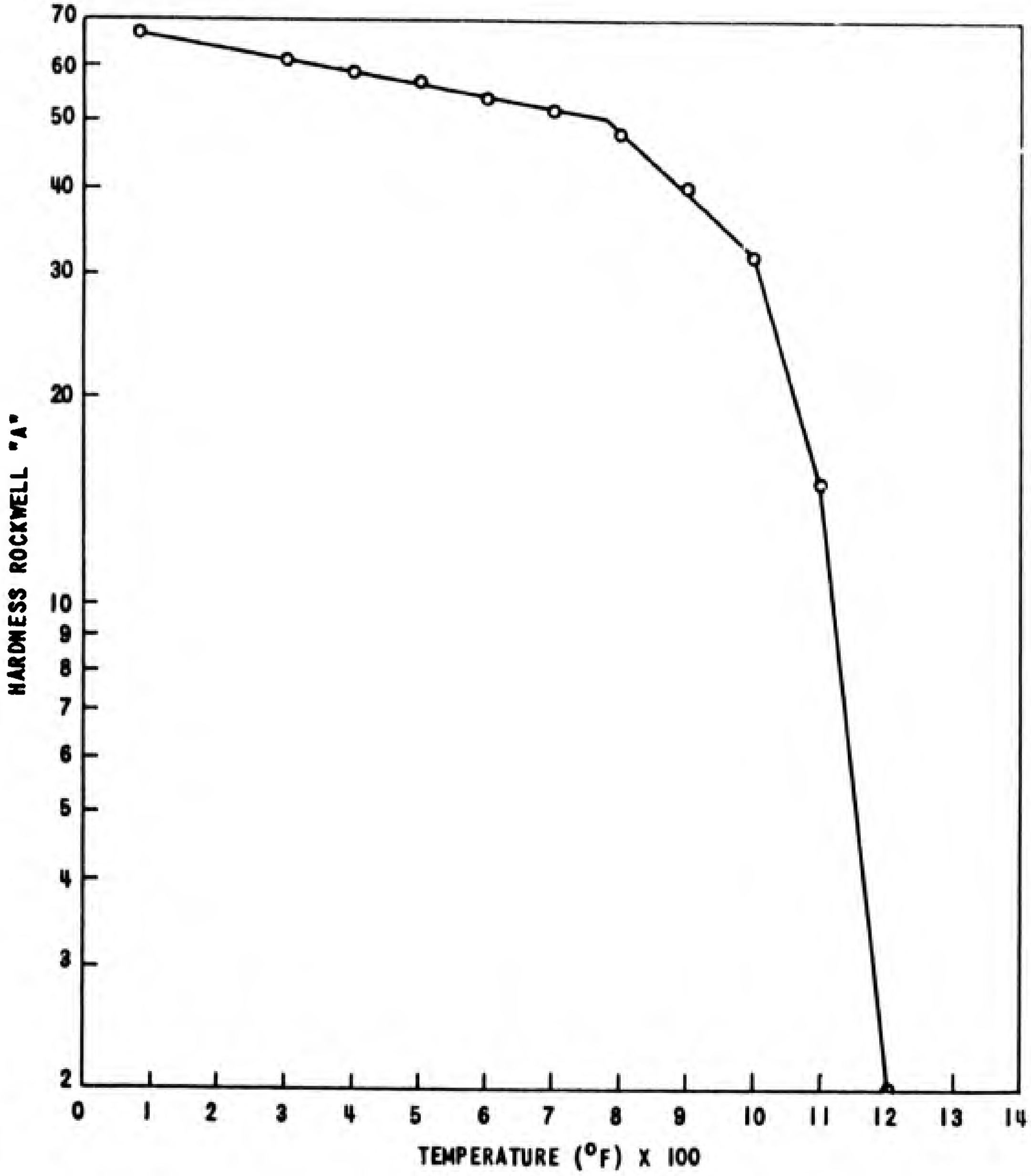
EFFECT OF TEMPERATURE ON THE HARDNESS O CI¡OM (RJIA2)

FIGURE 10



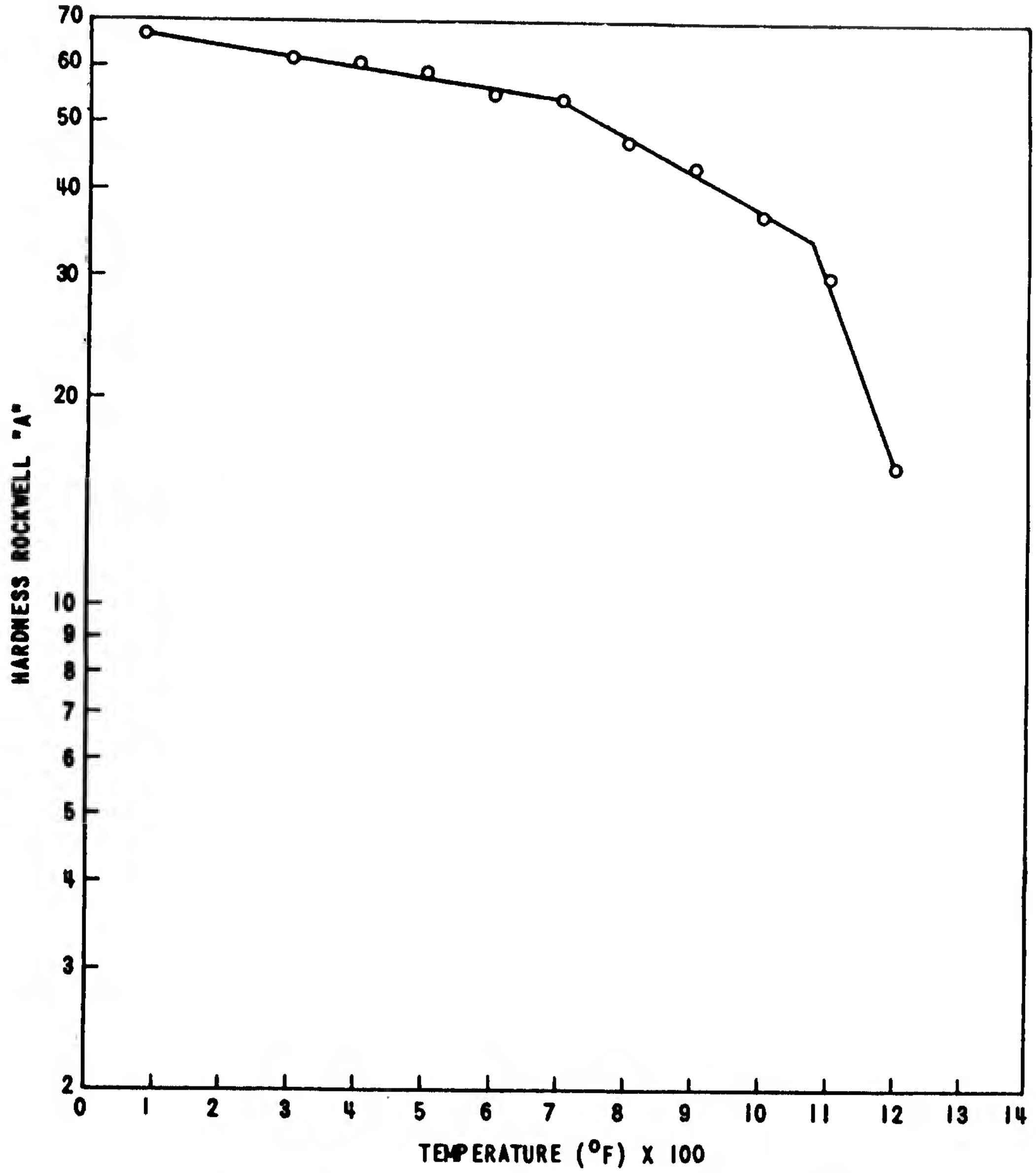
EFFECT OF TEMPERATURE ON THE HARDNESS OF C130AM (RH1B2)

FIGURE 11



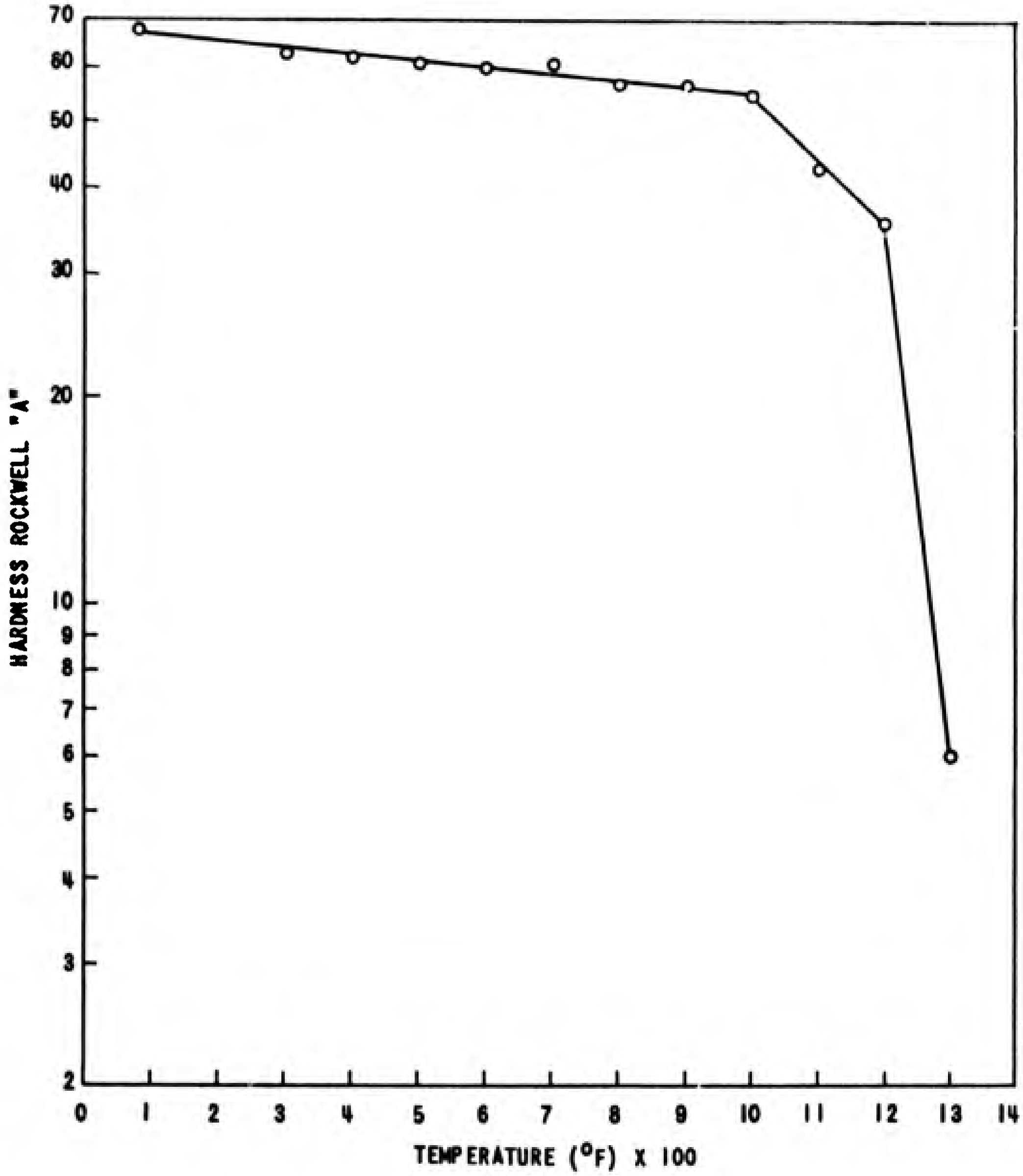
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti150A (TH1J2)

FIGURE 12



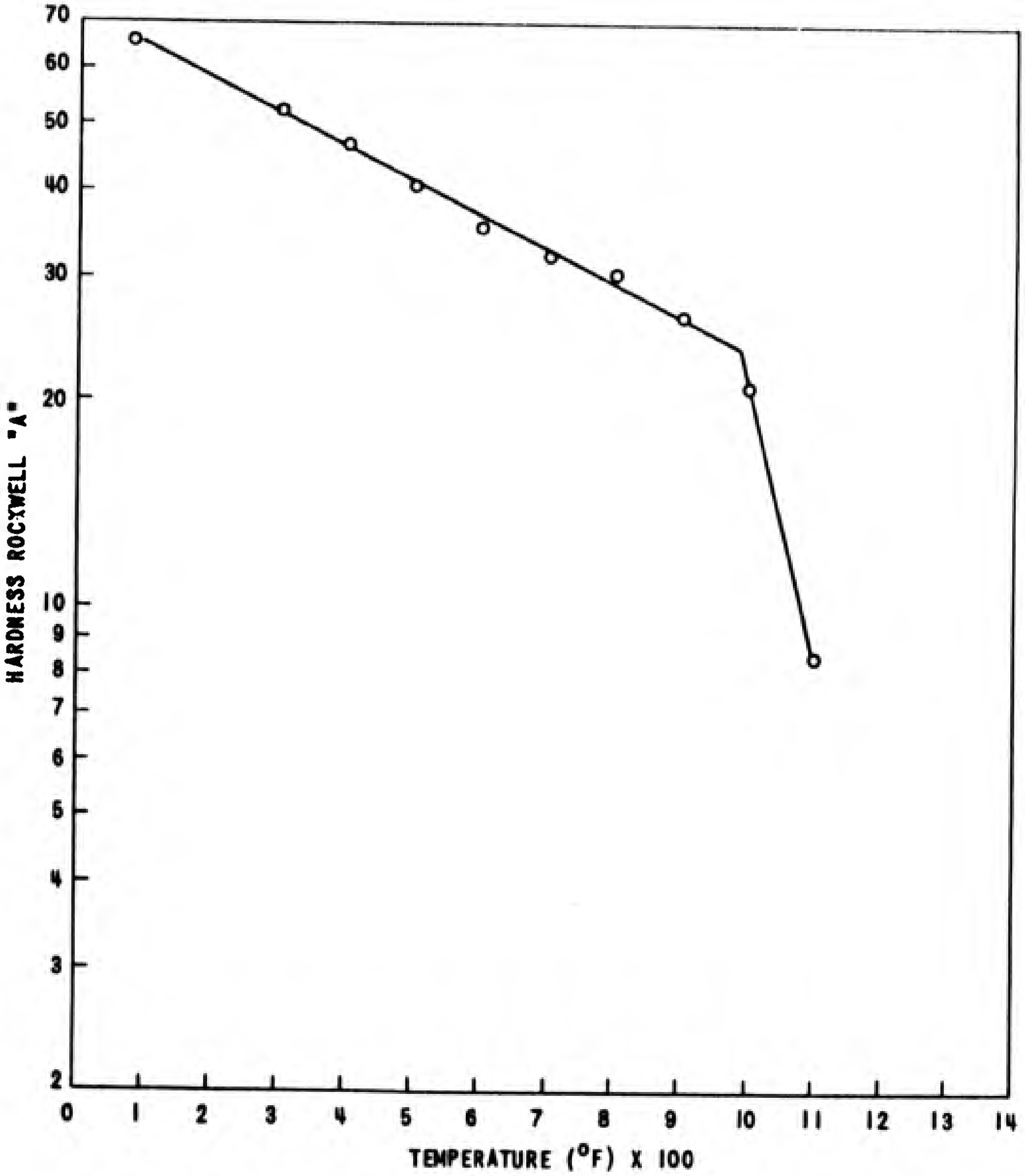
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti150A (TXF2)

FIGURE 13



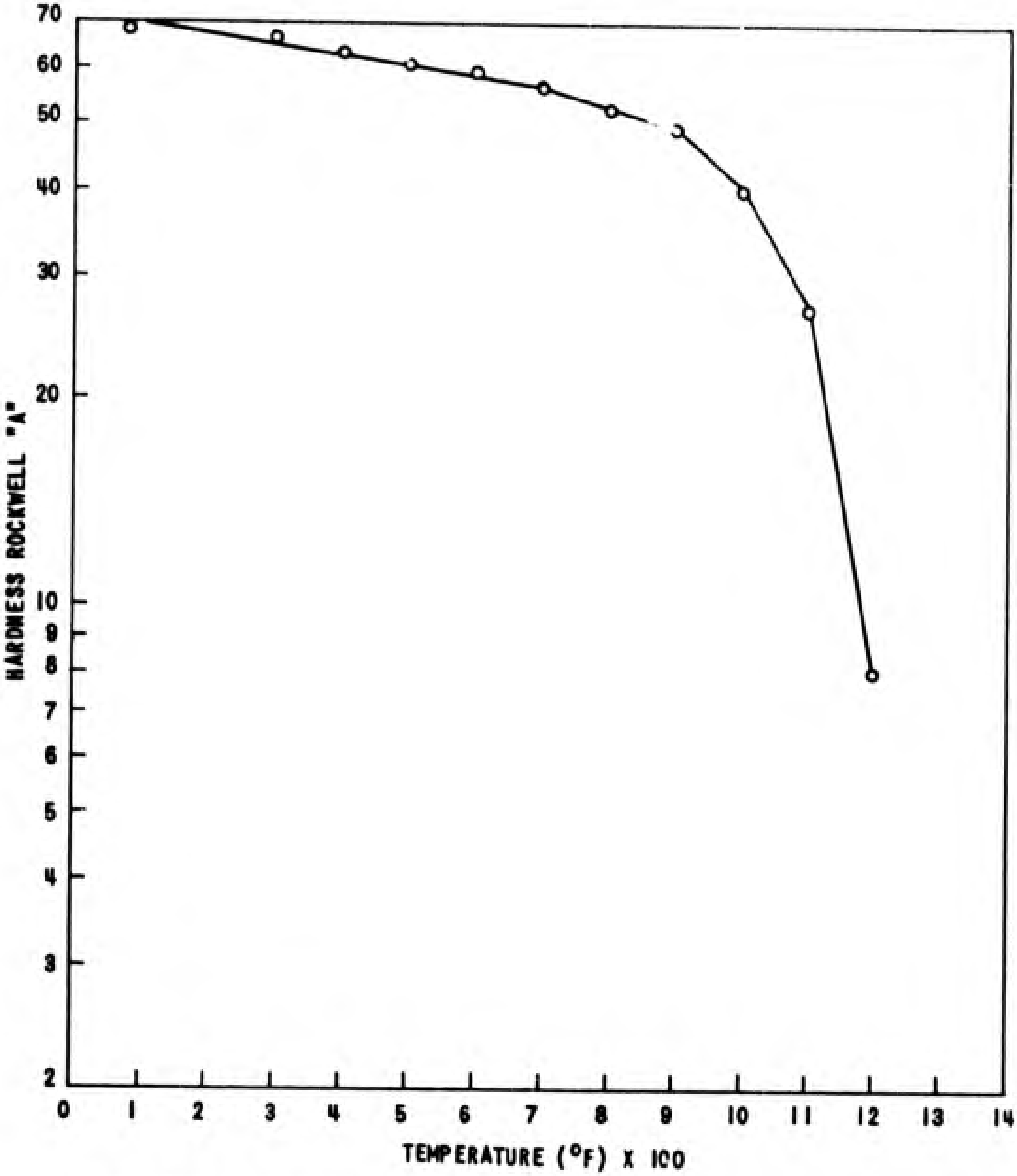
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti150B (THIL5)

FIGURE 14



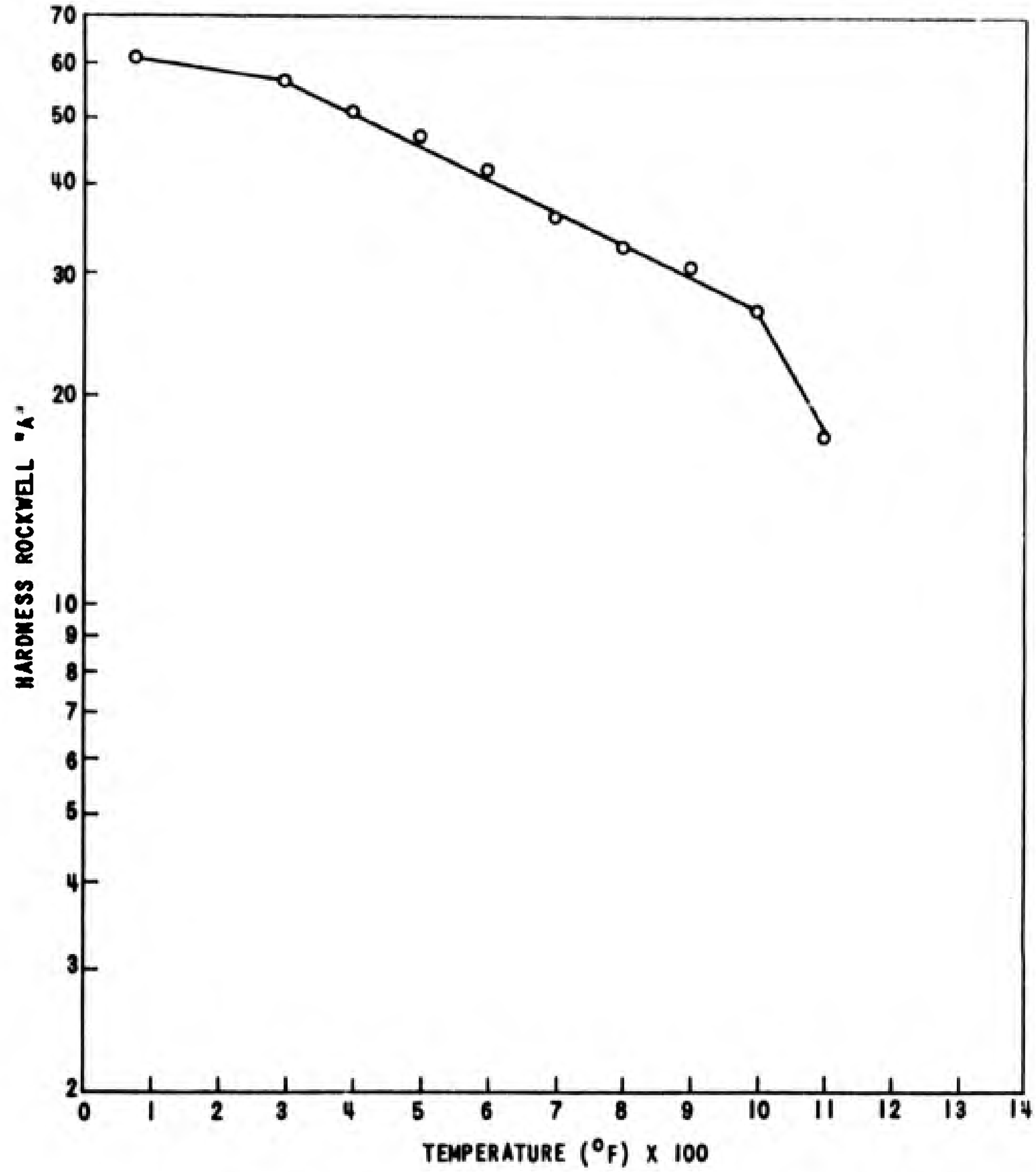
EFFECT OF TEMPERATURE ON THE HARDNESS OF A55 (RHICI)

FIGURE 15



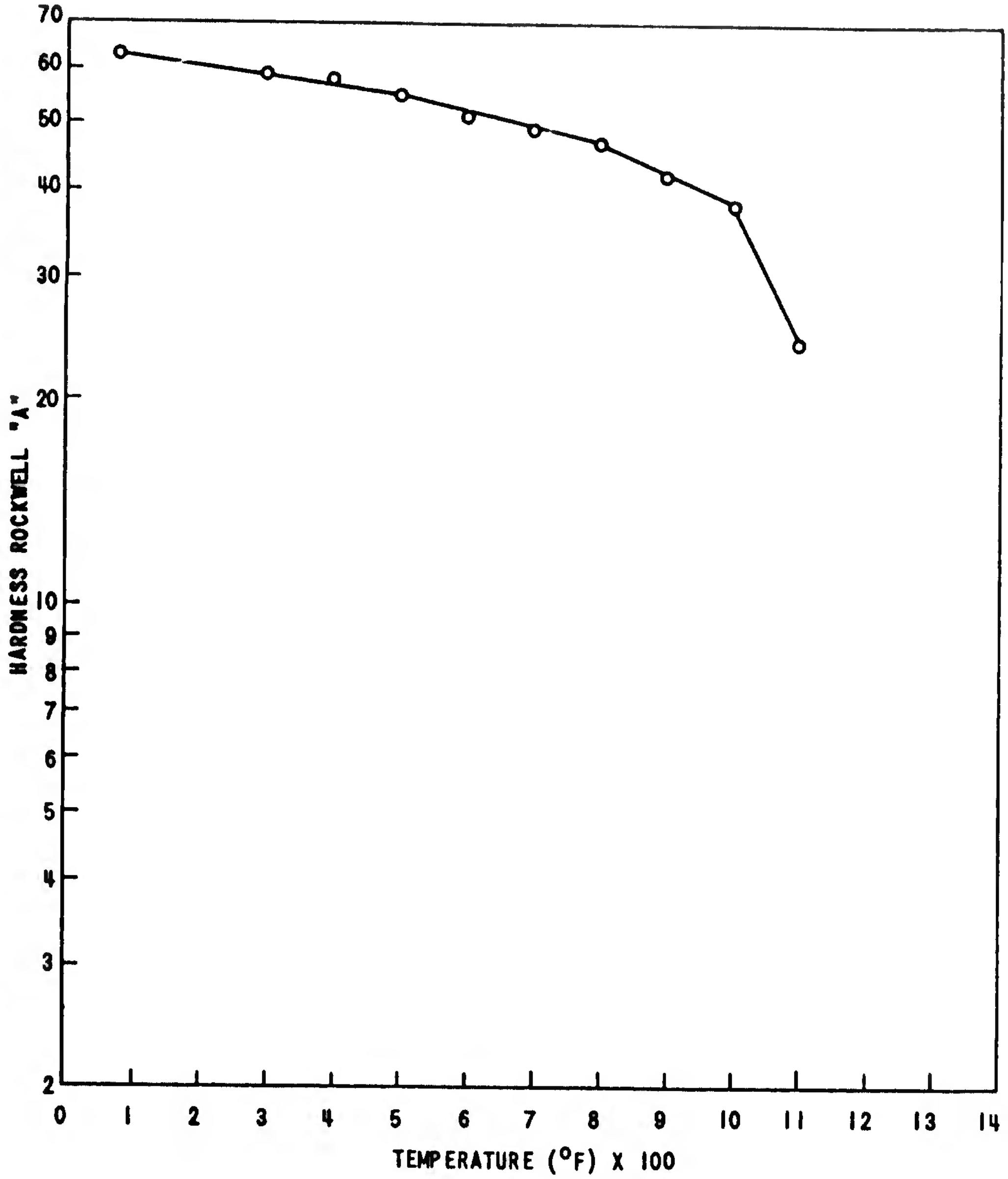
EFFECT OF TEMPERATURE ON THE HARDNESS OF C110M (RH1E2)

FIGURE 16



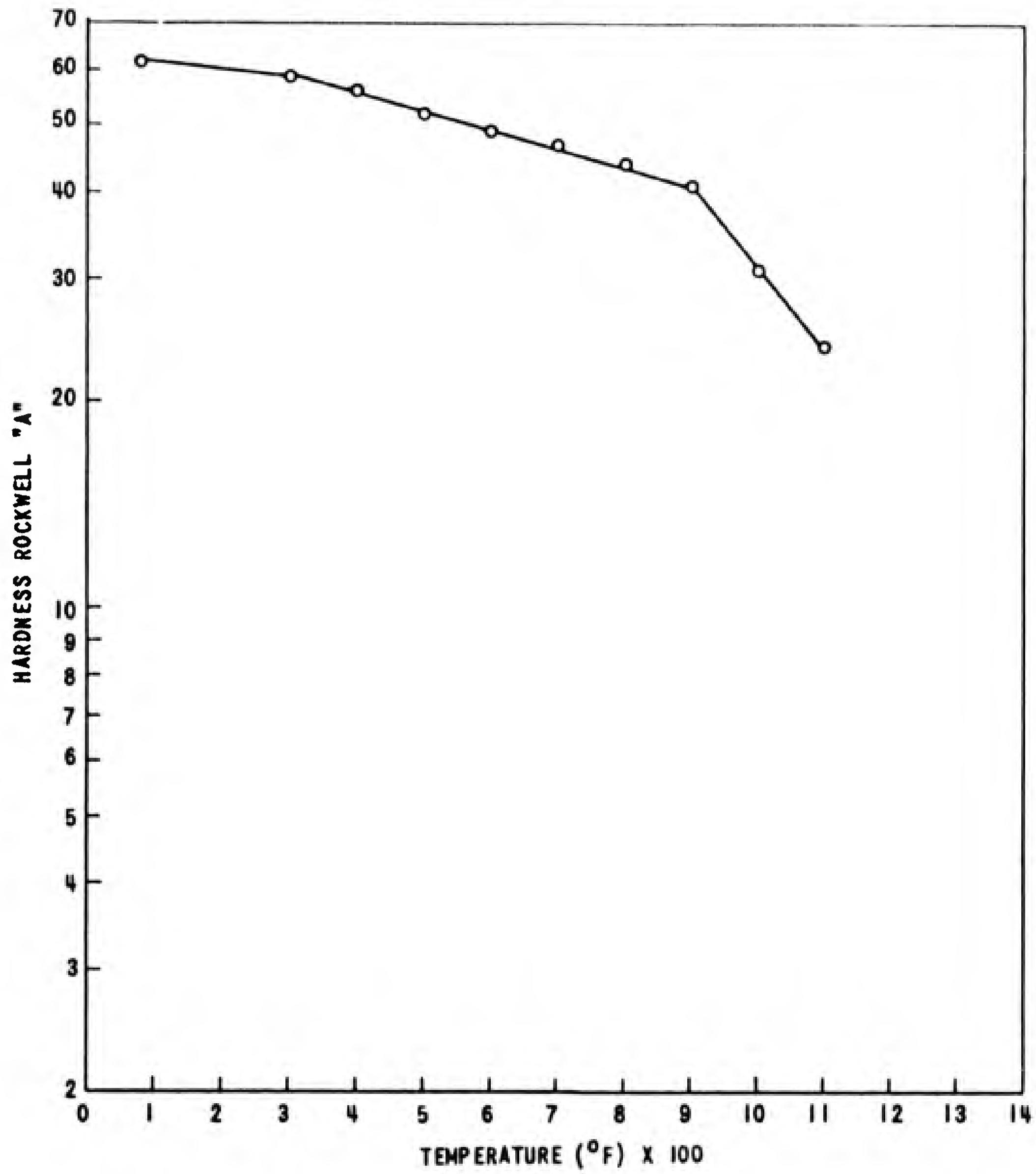
EFFECT OF TEMPERATURE ON THE HARDNESS OF RC70 (RHIDI)

FIGURE 17



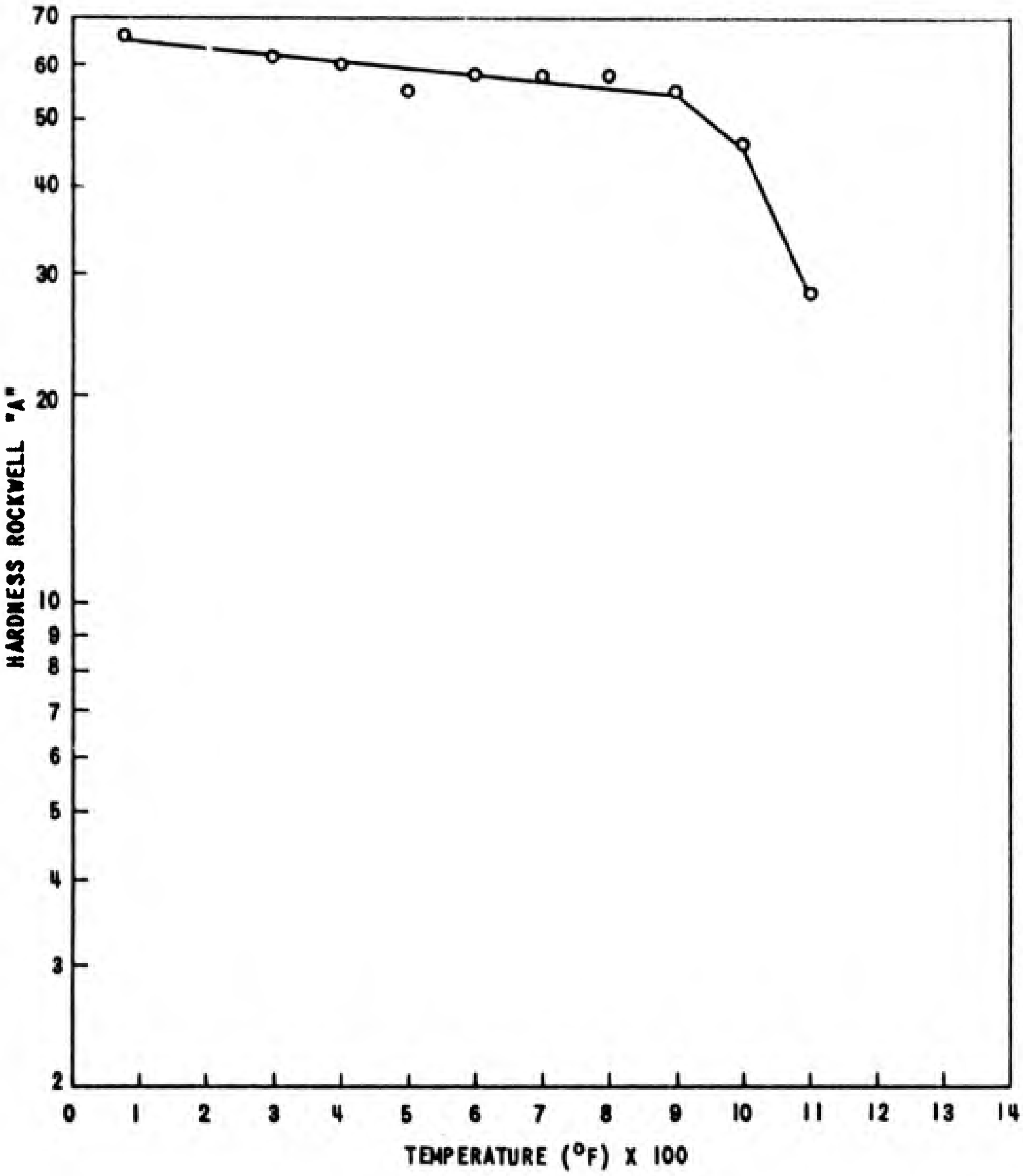
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-3.8Cr-1.5Fe (RS14)

FIGURE 18



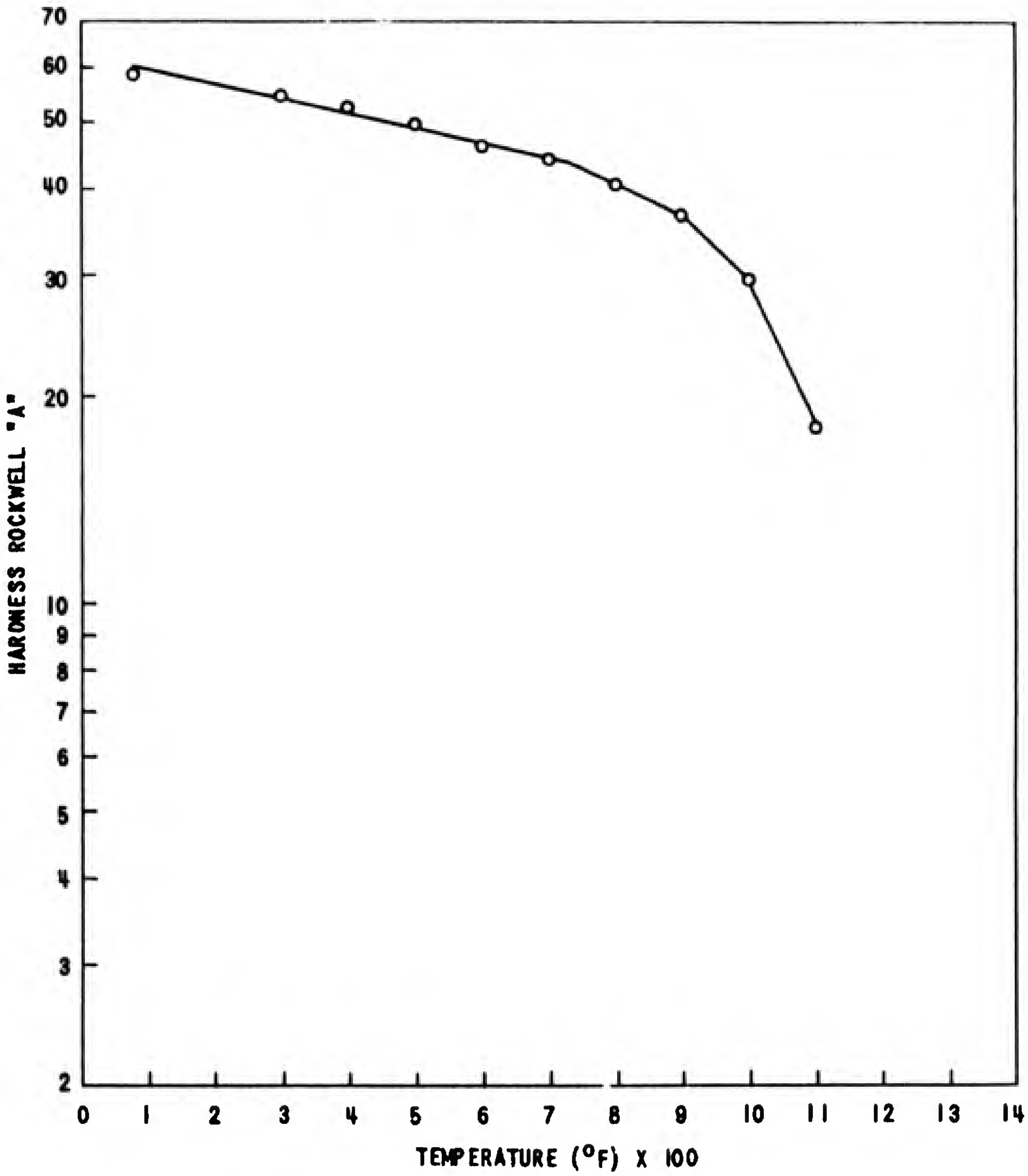
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-3.4Al-1.5Sn (R26)

FIGURE 19



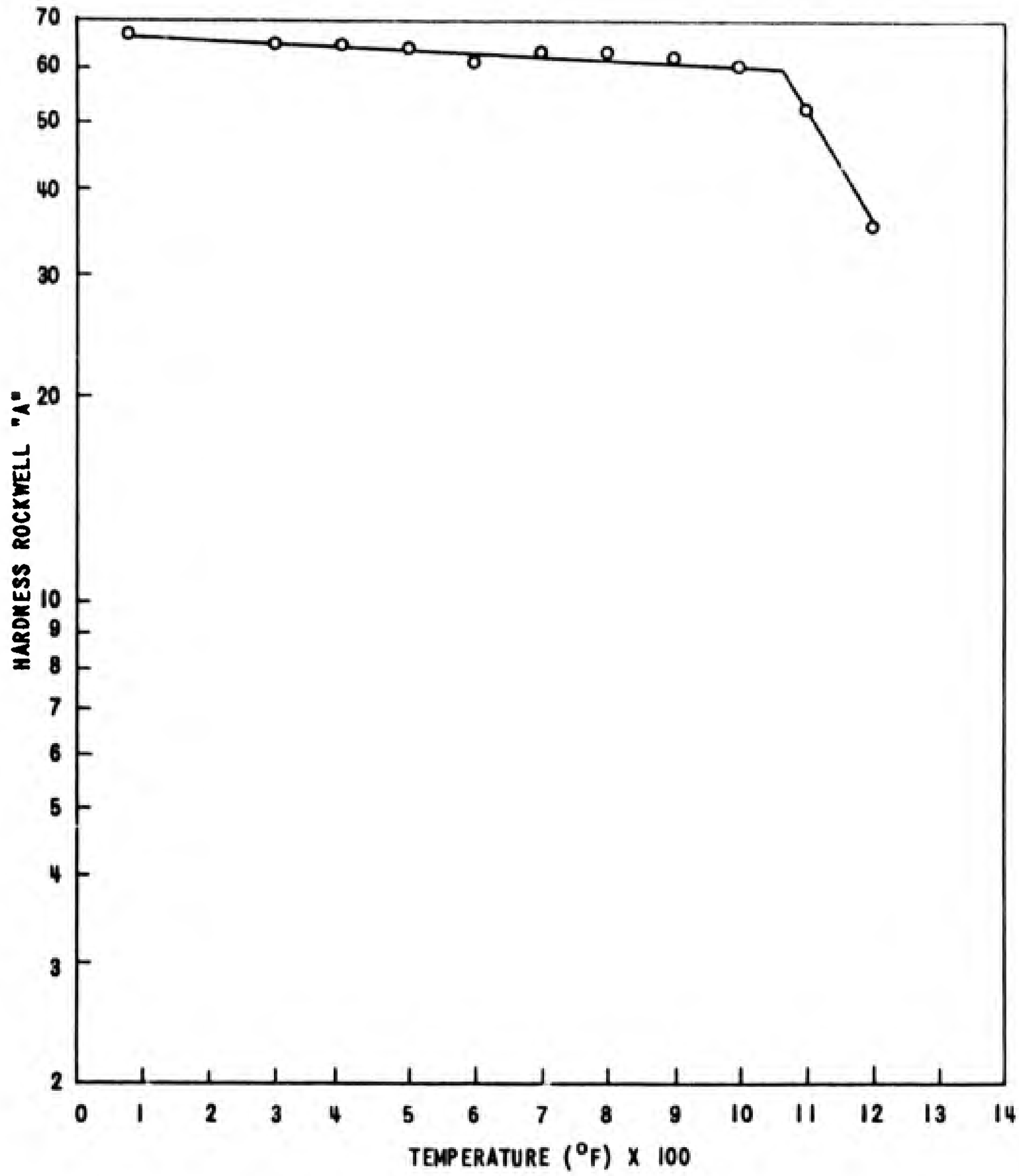
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-6.8Mn-4.3Mo-3.9Cr (R110)

FIGURE 20



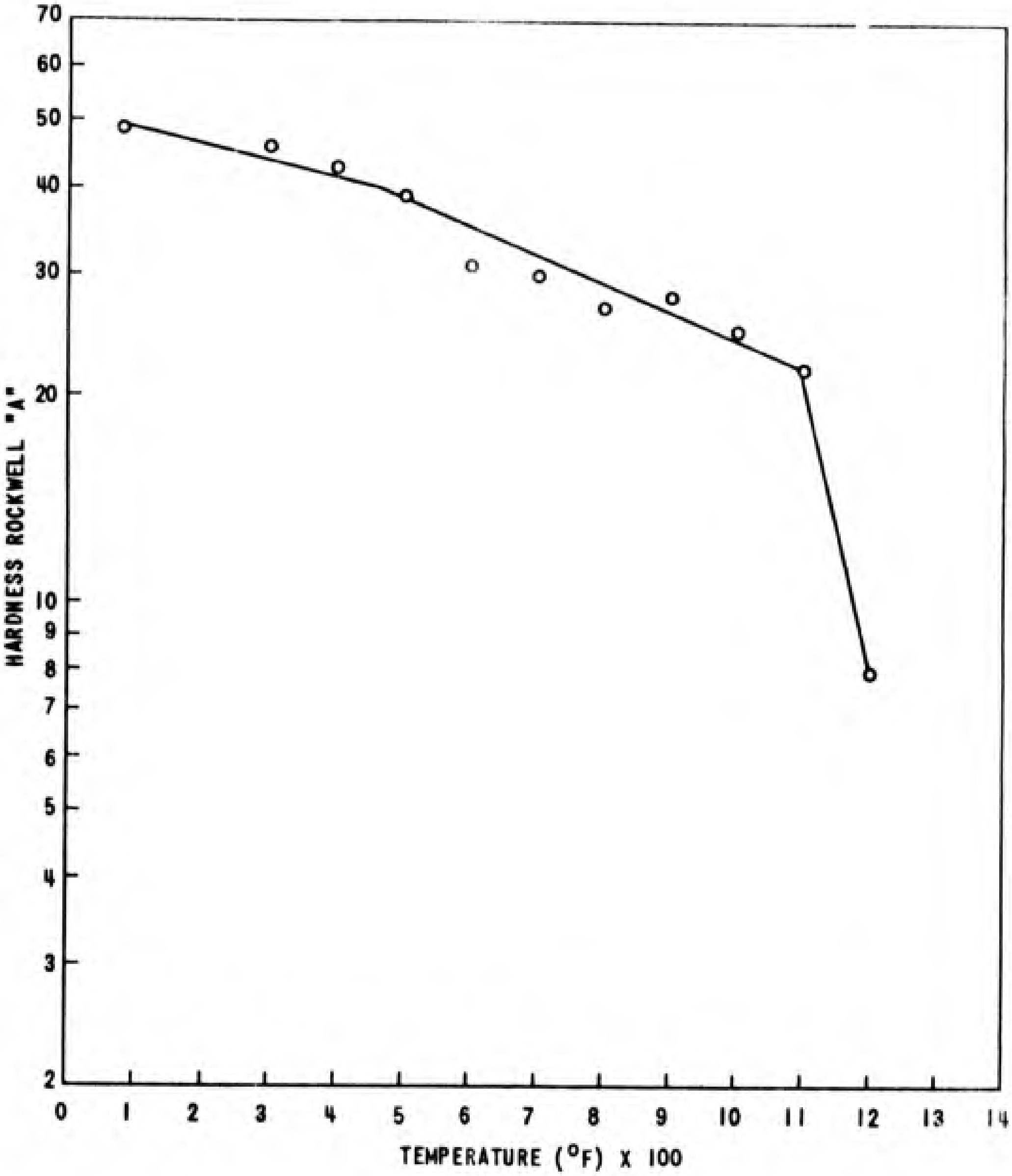
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-3.8Cr-2.5Mo (AZ5)

FIGURE 21



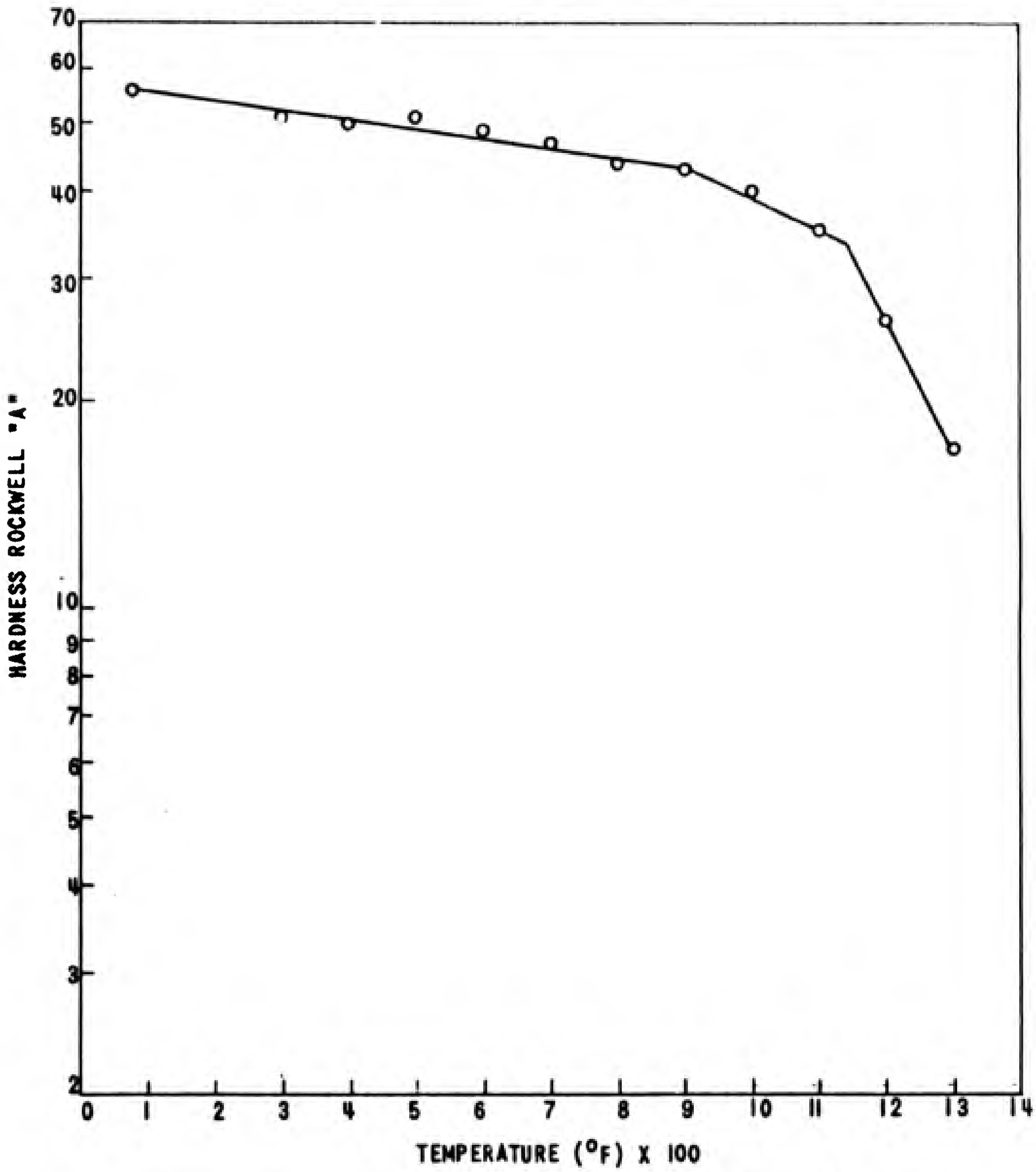
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-5.4Fe-11.8Cr (K100)

FIGURE 22



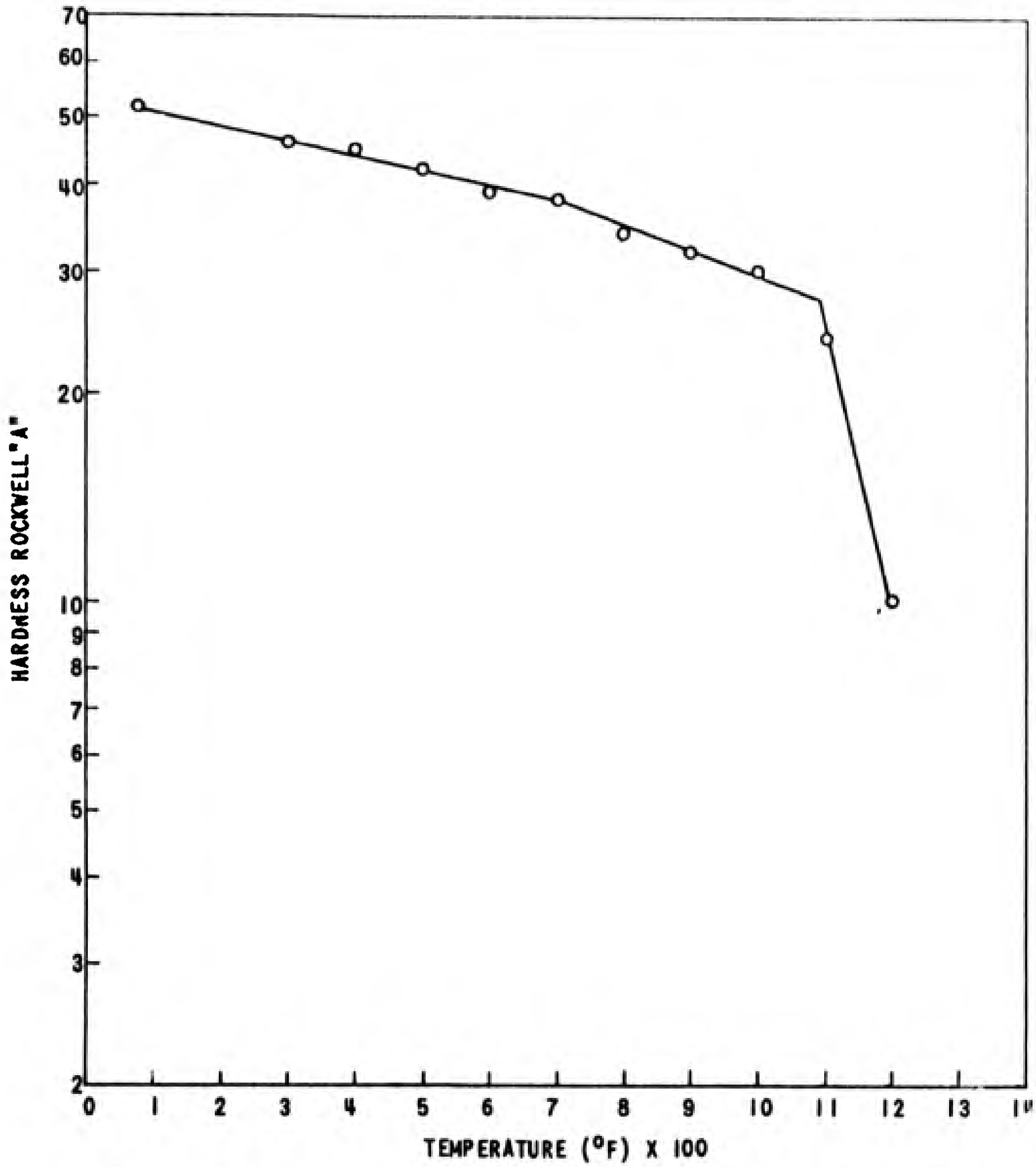
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-0Zr (TZI)

FIGURE 23



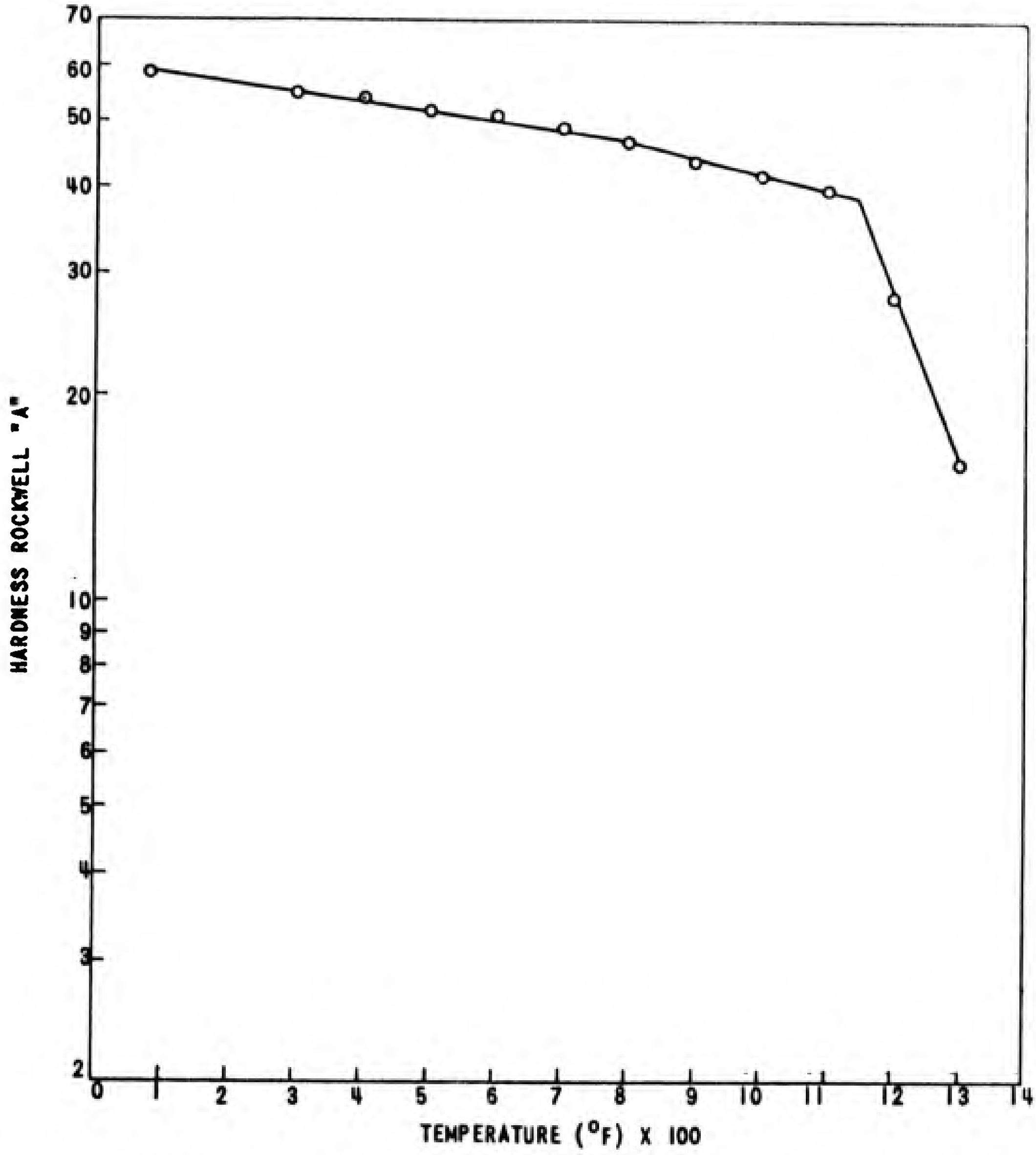
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-5Zr (TZ2)

FIGURE 24



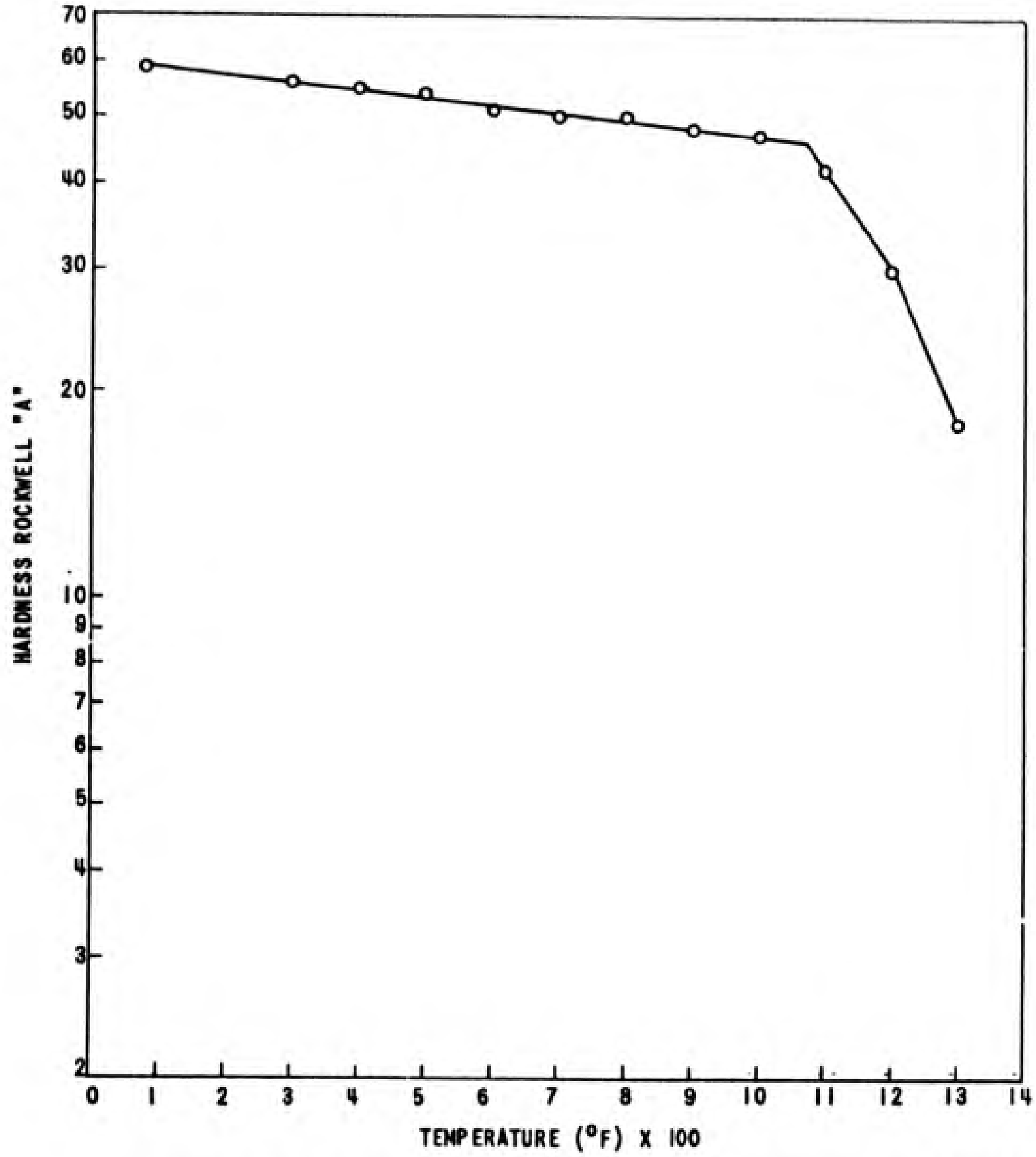
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-9.4Zr (TZ3)

FIGURE 25



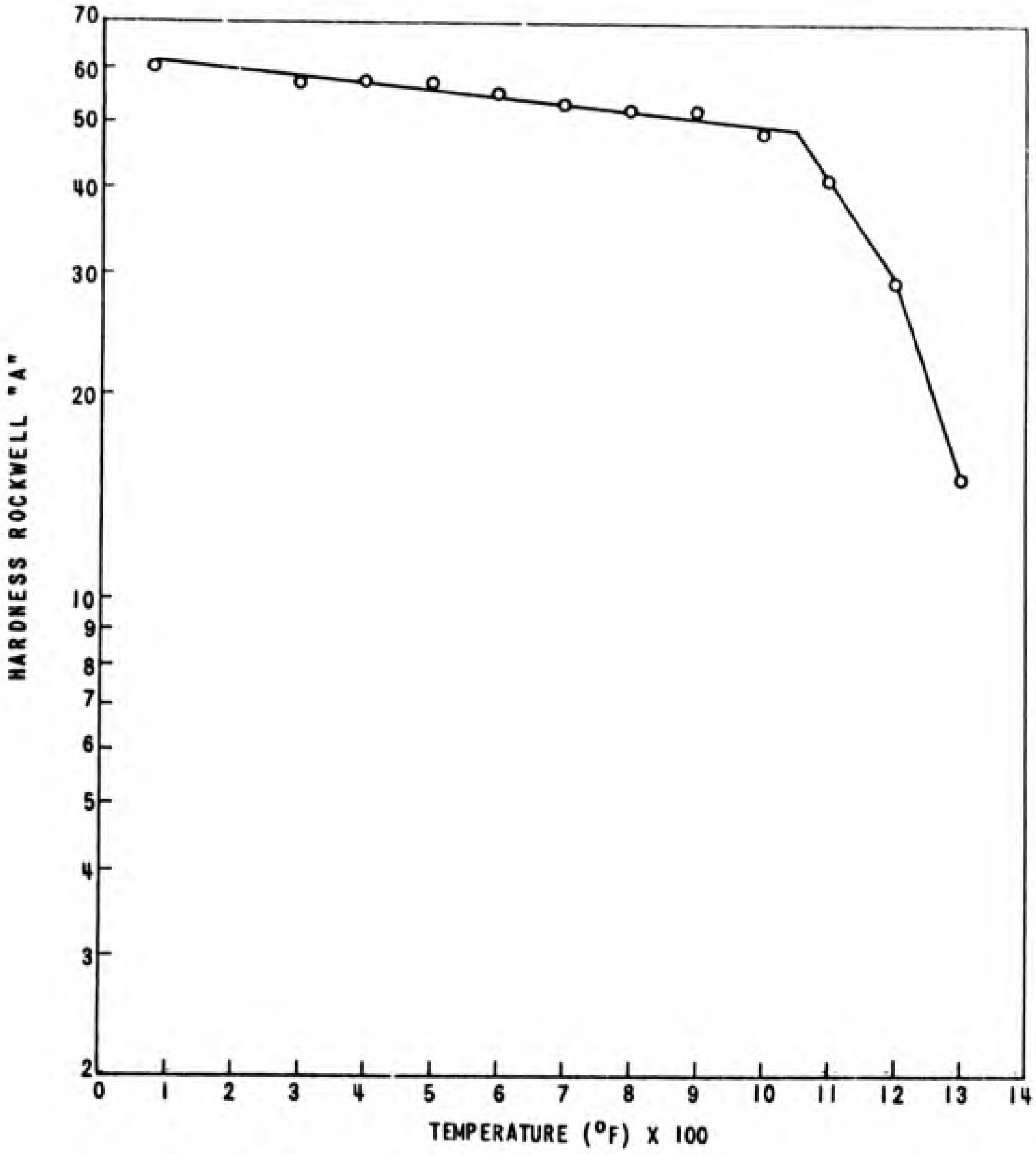
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-13.8Zr (TZ4)

FIGURE 26



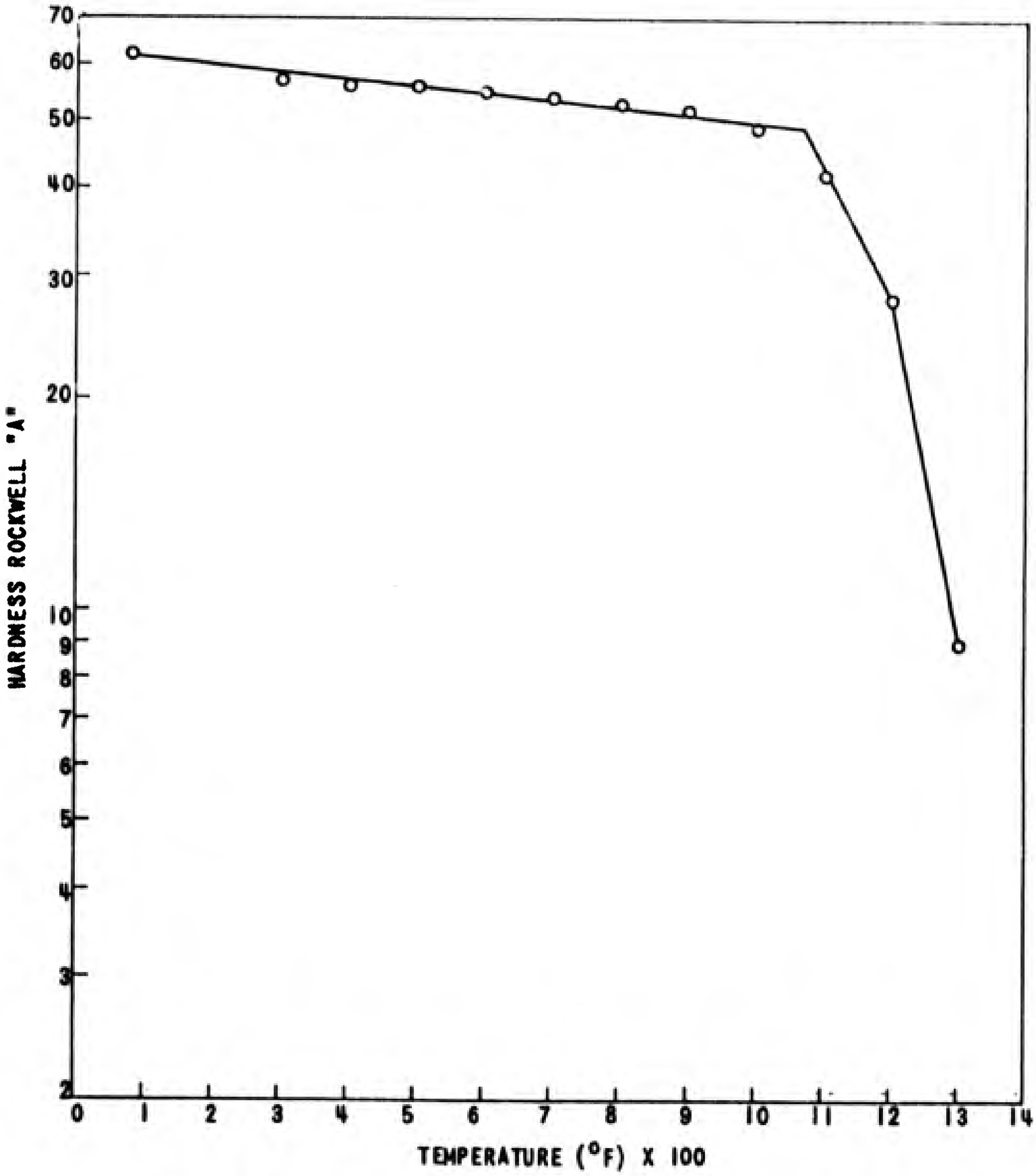
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-24.9Zr (TZ5)

FIGURE 27



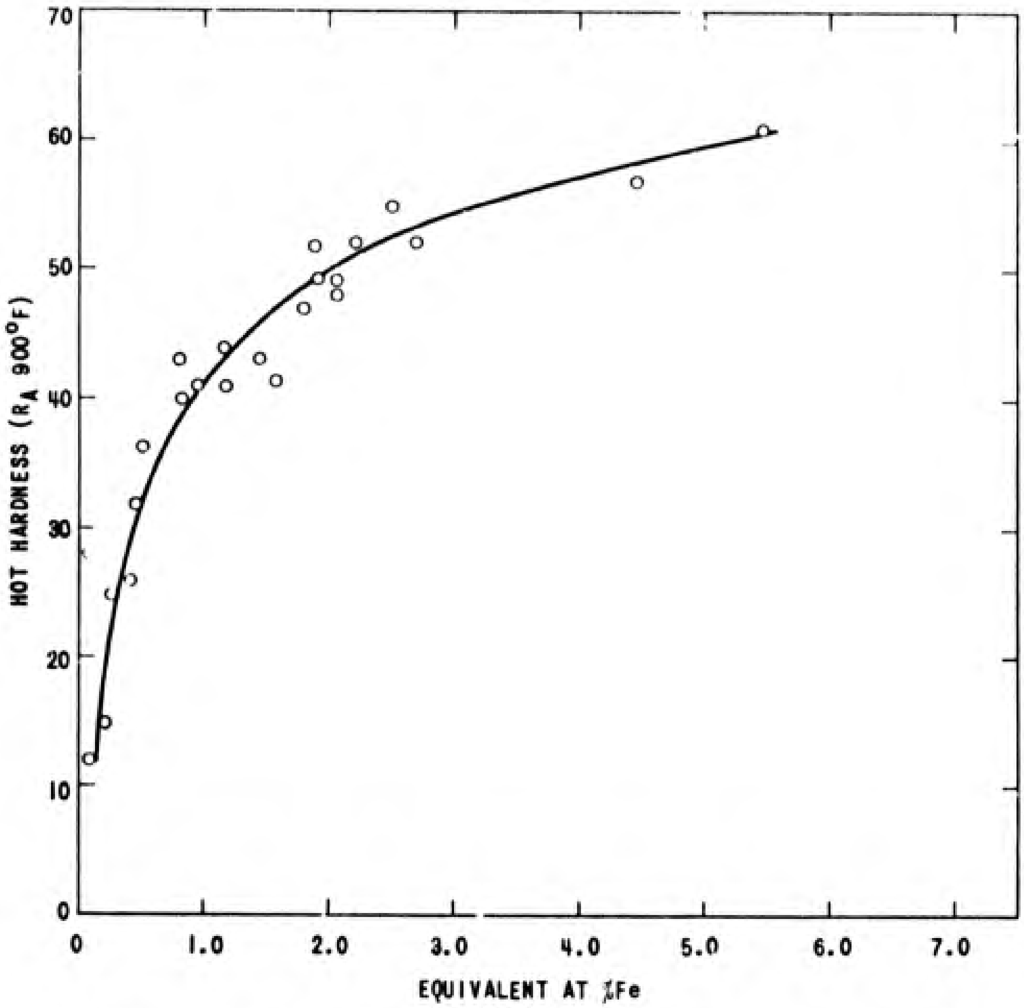
EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-26.3Zr (TZ6)

FIGURE 28



EFFECT OF TEMPERATURE ON THE HARDNESS OF Ti-31.5Zr (TZ7)

FIGURE 29



EFFECT OF CHEMICAL COMPOSITION ON THE HOT HARDNESS OF TITANIUM AT 900°F

FIGURE 30

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The influence of alloying elements in promoting resistance to softening was evaluated at 900°F. Iron was found to be the most effective with the other elements being arranged in order of decreasing effect, as follows: manganese, molybdenum, aluminum, zirconium, and chromium.

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