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URANIUM-TREATED HIGH CARBON WIRE ROPE STEEL

by

R. F. KNIGHT & G. P. CONTRACTOR

PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

The effect of uranium on commercially produced fine-grained high carbon steel was investigated. Uranium additions equivalent to 2-1/4 lb per ton were made to 6-ton ingots during teeming, the recovery being in the order of 70%. The ingots were rolled and drawn to fine wires (0.016, 0.017, 0.019 and 0.020 in. diameter) without difficulty. The distribution of uranium was uniform for all practical purposes, although the autoradiographs of the longitudinal billet sections indicated that uranium had a tendency to concentrate towards the bottom of the ingot.

It was found that the uranium content of about 0.10% in 0.75% carbon steel was neither detrimental nor beneficial with respect to tensile properties, room temperature V-notch impact toughness, hardenability, torsion characteristics, or response to ageing treatment. However, there were clear indications that uranium increased the notch sensitivity of the steel as determined from fatigue test data. The presence of uranium also resulted in a slight decrease in the resistance to corrosion fatigue.

The addition of uranium significantly affected the morphology of sulphide inclusions which were present as multiple blocky sulphides rather than long stringer type.

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INTRODUCTION

In the course of preliminary studies of the effect of uranium on carbon steels it was observed (1, 2) that uranium may have some beneficial effect on the fatigue limit of medium carbon steels containing up to 0.40% carbon. Although the findings of the above studies were only tentative, great interest was shown by steel producers, both in Canada and the United States, on the influence of uranium additions to iron and steel.

Several commercial heats containing uranium have been made in this country for large scale experimentation and field trials of the finished products.

This investigation is one more example of large scale experimentation and deals with the effect of uranium on a commercial fine-grained 0.75% carbon steel made by Dominion Steel and Coal Corporation, Limited (DOSCO), Sydney, Nova Scotia, for the manufacture of experimental aircraft wire rope. The basic objective of this study was to examine the mechanical properties, including fatigue strength, of uranium-treated wire rope and to evaluate its field performance. This report embodies the results of laboratory tests and deals with the mechanical properties, dry and corrosion fatigue characteristics, V-notch impact toughness, hardenability, autoradiographic examination, uranium distribution and other studies. The results of the field service tests being conducted by the rope manufacturers are not yet available.

PRODUCTION AND PROCESSING

As reported in Physical Metallurgy Division Internal Report PM-V-62-12, April 10, 1962, a commercial open hearth heat of aluminum-killed high carbon steel was made for the production of wire rope. The target analysis was 0.76 to 0.80% carbon and 0.60 to 0.75% manganese. Big-end-up ingot moulds with hot tops were employed. In all, 41-1/2 ingots, each weighing 11,550 lb (24 in. x 26 in. x 72 in. and 9,780 lb, excluding hot top) were teemed. Ingot 18 was used for the determination of the properties of the uranium-free steel. Uranium additions were made to Ingots 4 and 5 during teeming. In all, 13-1/2 lb of uranium metal (2-1/4 lb per ton) was added to each ingot in 1 lb lots wrapped in aluminum foil.

The test ingots were rolled to 6 in. x 5 in. blooms and then further reduced to 1-3/4 in. square billets. The billets were then rolled to 7/32 in. diameter rods. As reported in Physical Metallurgy Division Internal Report PM-V-62-20, these rods were patented and drawn to 0.125 in. diameter wire. This wire was patented, drawn to four base sizes, re-patented, galvanized and drawn into four final sizes, viz., 0.016, 0.017, 0.019 and 0.020 in. diameter. Uranium-bearing and uranium-free wires were tagged RALU and RAL, respectively, for identification. These wires were used to manufacture experimental aircraft wire rope.

The wire rope as well as samples selected from various phases of the manufacturing process were subjected to testing.

CHEMICAL COMPOSITION

The results of chemical analyses carried out by the Mines Branch and by DOSCO are listed in Table 1.

The uranium analyses indicated a slightly higher uranium recovery for Ingot 5 (75.6%) than for Ingot 4 (70%). The overall uranium recovery was 72%. No massive segregation of uranium was indicated by chemical analysis.

TABLE 1

Results of Chemical Analyses

Sample Identification	C	Mn	Si	S	P	Cr	Acid Insol Al	Total Al	N	Vacuum Fusion Nitrogen	Vacuum Fusion Oxygen	Total U
Spoon*	0.75	0.63	0.20	0.021	0.015	-	-	-	-	-	-	**
Preliminary - Ingot 4	-	-	-	-	-	-	-	-	-	-	-	0.079
Preliminary - Ingot 5	-	-	-	-	-	-	-	-	-	-	-	0.085
Ingot 18 - Top	0.78	0.63	0.21	0.027	0.016	0.04	<0.001	0.03	0.005	0.002	0.004	**
Ingot 18 - Bottom	0.73	0.63	0.20	0.027	0.016	0.04	<0.001	0.03	0.005	-	-	**
Ingot 4 - Top	0.74	0.64	0.22	0.026	0.015	0.04	0.001	0.04	0.005	0.003	0.004	0.075
Ingot 4 - Middle	-	-	-	-	-	-	-	-	-	-	-	0.082
Ingot 4 - Bottom	0.79	0.63	0.20	0.026	0.014	0.04	0.001	0.04	0.003	-	-	0.079
Ingot 4 - Bottom	0.76	0.62	0.22	0.026	0.014	0.04	0.001	0.04	0.005	-	-	0.081
Ingot 5 - Top	0.76	0.65	0.22	0.026	0.014	0.04	0.001	0.03	0.005	0.003	0.005	0.084
Ingot 5 - Middle	-	-	-	-	-	-	-	-	-	-	-	0.084
Ingot 5 - Bottom	0.77	0.62	0.22	-	-	0.04	<0.001	0.04	0.005	0.004	0.004	0.085
Ingot 5 - Bottom	0.70	0.63	0.21	0.024	0.014	0.04	<0.001	0.04	0.006	-	-	0.093
RAL - Coil 1*	0.74	0.67	0.21	0.025	0.010	-	-	-	-	-	-	**
RAL - Coil 2*	0.75	0.67	0.21	0.025	0.010	-	-	-	-	-	-	**
RALU - Coil 1*	0.75	0.66	0.21	0.025	0.010	-	-	-	-	-	-	-
RALU - Coil 2*	0.76	0.66	0.21	0.024	0.010	-	-	-	-	-	-	-
RALU - 0.016 wire	-	-	-	-	-	-	-	-	-	-	-	0.079
RALU - 0.017 wire	-	-	-	-	-	-	-	-	-	-	-	0.084
RALU - 0.019 wire	-	-	-	-	-	-	-	-	-	-	-	0.080
RALU - 0.020 wire	-	-	-	-	-	-	-	-	-	-	-	0.075
Ingot 18 - Average	0.75	0.65	0.21	0.025	0.013	0.04	<0.001	0.03	0.005	0.002	0.004	**
Ingot 4 - Average	0.76	0.63	0.21	0.026	0.014	0.04	0.001	0.04	0.004	0.003	0.004	0.079
Ingot 5 - Average	0.75	0.63	0.21	0.025	0.014	0.04	<0.001	0.04	0.005	0.004	0.005	0.086
U-Bearing - Average	0.75	0.66	0.21	0.025	0.013	0.04	0.001	0.04	0.005	0.003	0.004	0.081

* - DOSCO'S Results
** - Uranium not added.

SEGREGATION

The distribution of uranium was investigated by autoradiography, deep-etching and sulphur printing techniques to determine whether any massive segregation of uranium had occurred. Figure 1 shows autoradiographic prints of transverse sections of billets from the top, middle and bottom of Ingots 4 and 5. Figures 2 and 3 show reproductions of the sulphur prints and the deep-etched sections of the above-mentioned transverse sections, respectively. It can be seen that the top billets contained remnants of primary pipe, and that uranium was concentrated in these zones. The evidence of uranium segregation in the upper part of the ingot was revealed by autoradiography and deep-etching at the edge of the top billet section of Ingot 4.

The increase in the number of finely dispersed light areas on the autoradiographs and the lessened response to sulphur printing of the sections from the bottom of the ingots indicated a slightly higher uranium content toward the bottom. This was further illustrated by autoradiographs of longitudinal sections from the top and bottom billets of Ingots 4 and 5, as shown in Figures 4 and 5. The increase in uranium segregation toward the bottom was evident, but the results of earlier work were insufficient to indicate whether or not this comparatively mild degree of segregation would affect the mechanical properties.

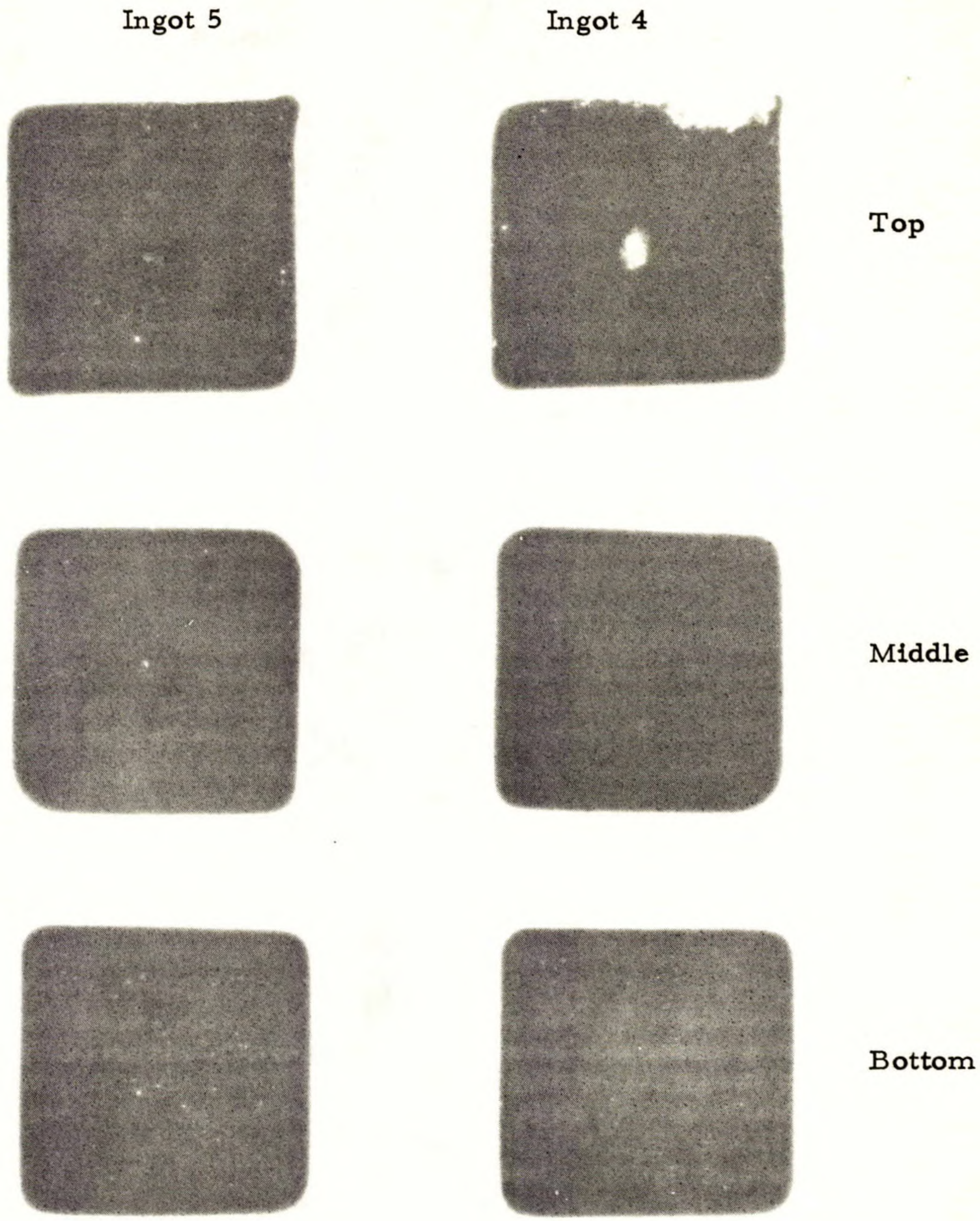


Figure 1. Autoradiographic prints of transverse billet sections representing top, middle and bottom of the uranium-bearing Ingots 4 and 5. (actual size).

Shows an accumulation of uranium segregate at the edge of the billet section from the top of Ingot 4, and a concentration of uranium at the remnants of primary pipe. Also evident is an increase in the number of finely dispersed light areas towards the bottom sections. Exposure: 48 hr.

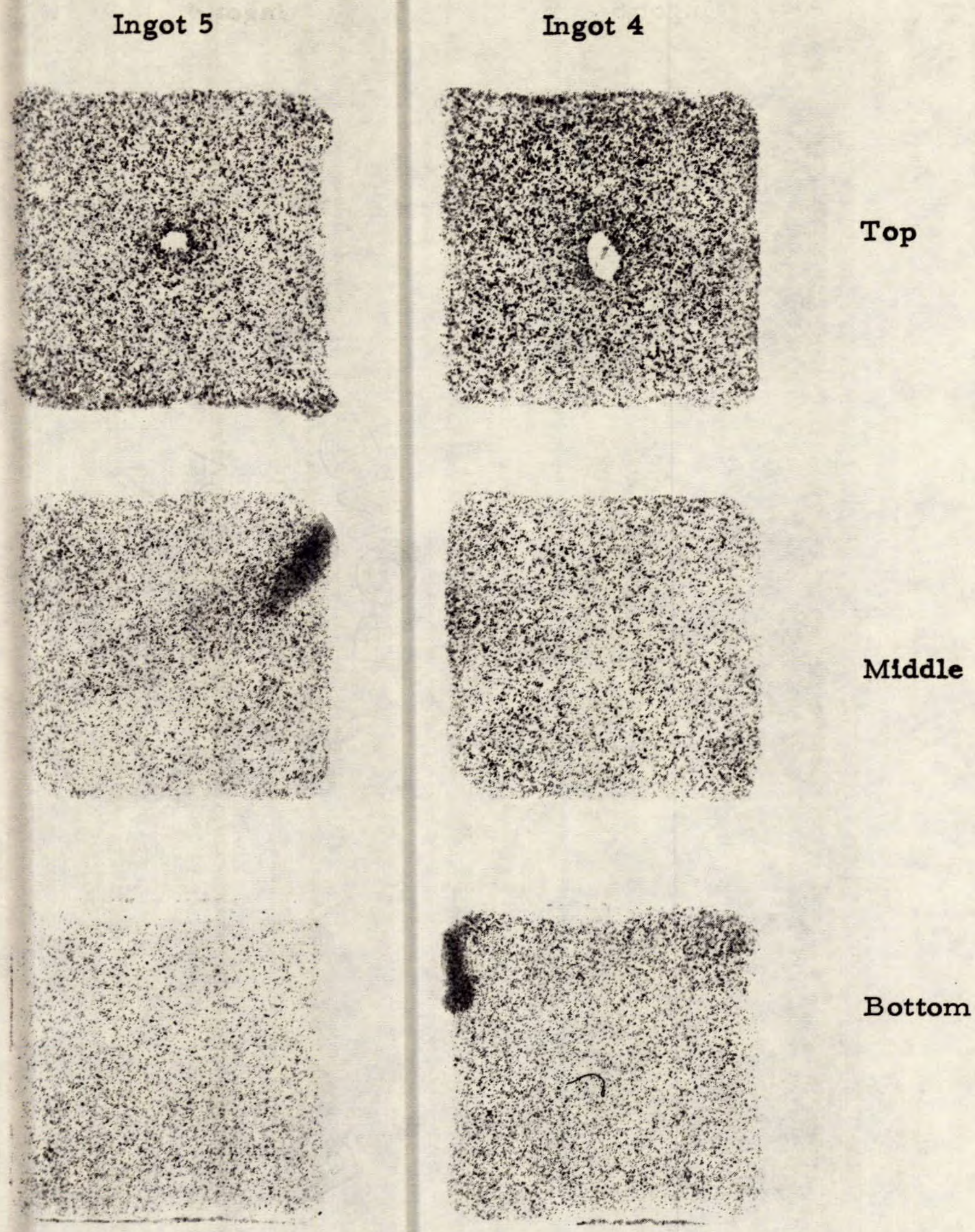


Figure 2. Reproduction of sulphur prints of transverse billet sections representing top, middle and bottom portions of the uranium-bearing Ingots 4 and 5. (approx. actual size).

Shows unprinted areas in top sections where a high content of uranium is associated with remnants of primary pipe. Also evident is a decrease in the sensitivity to sulphur printing towards the bottom.

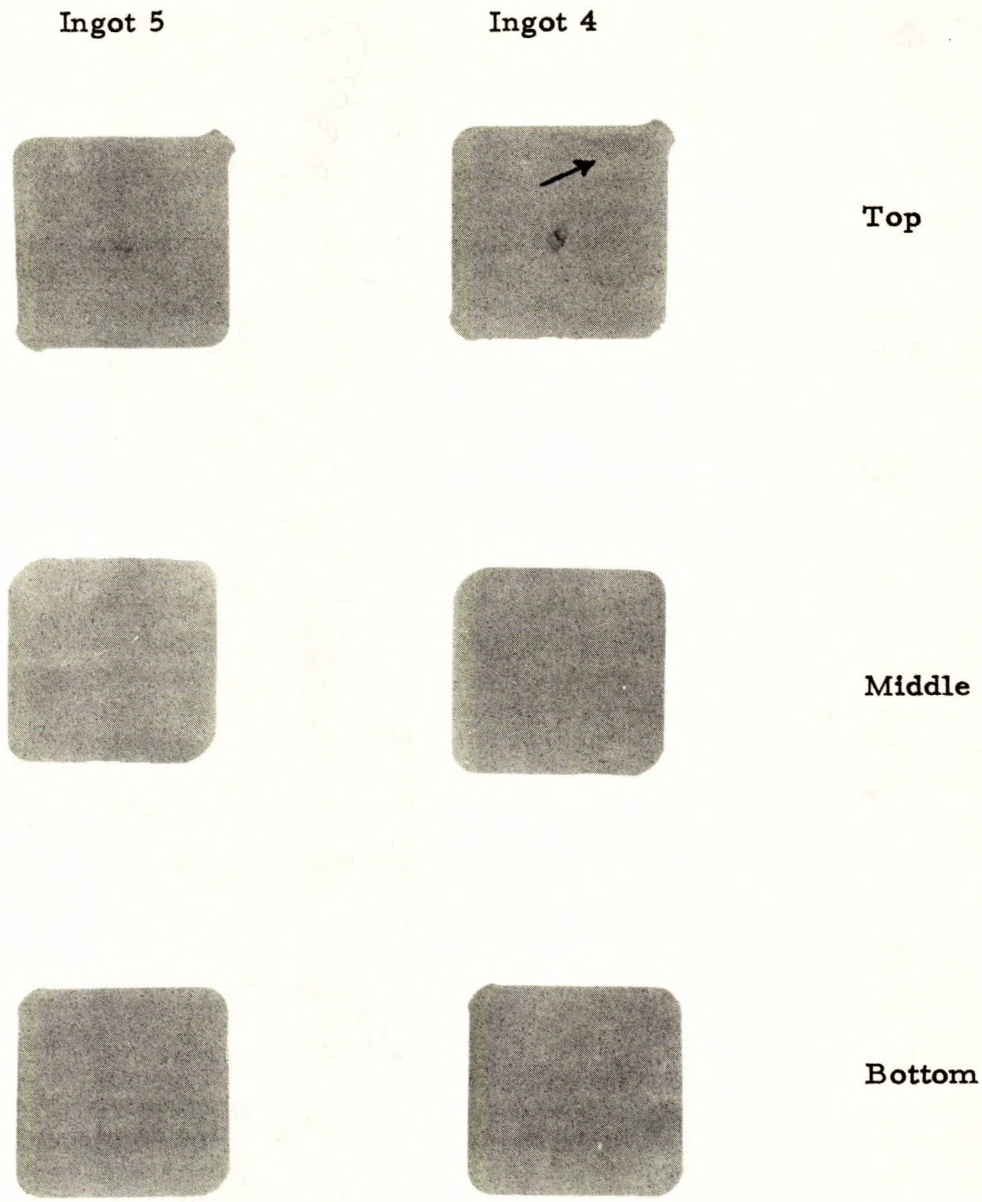
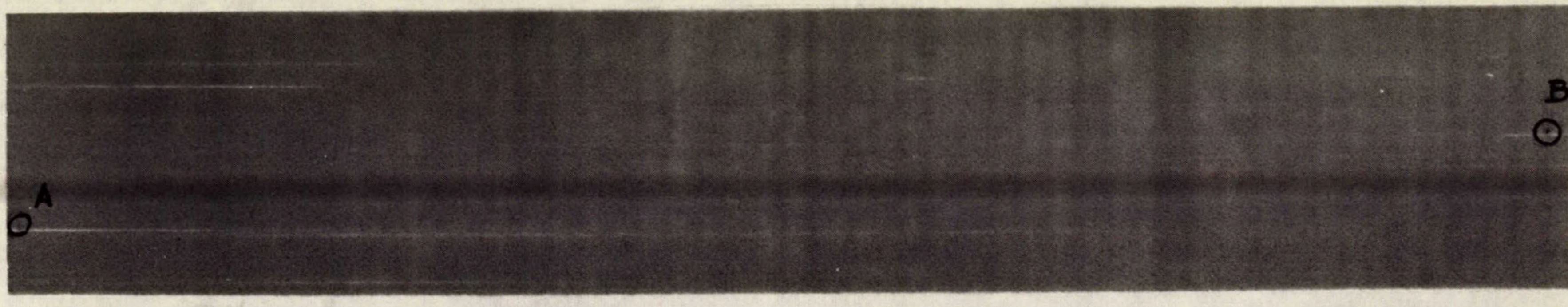
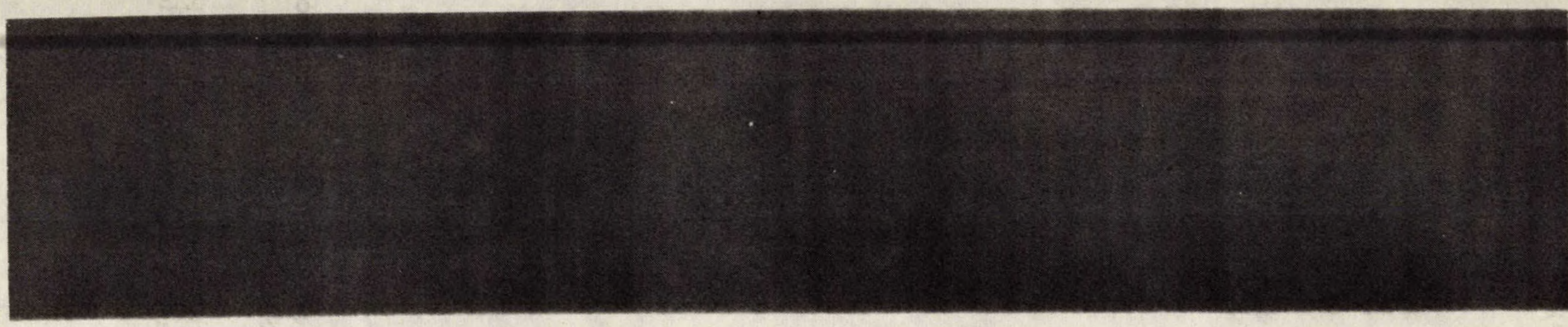


Figure 3. Reproduction of appearance of deep-etched transverse billet sections. (approx. X3/4).

Shows remnants of primary pipe and area of uranium segregate (arrow) at the edge of the top section from Ingot 4.

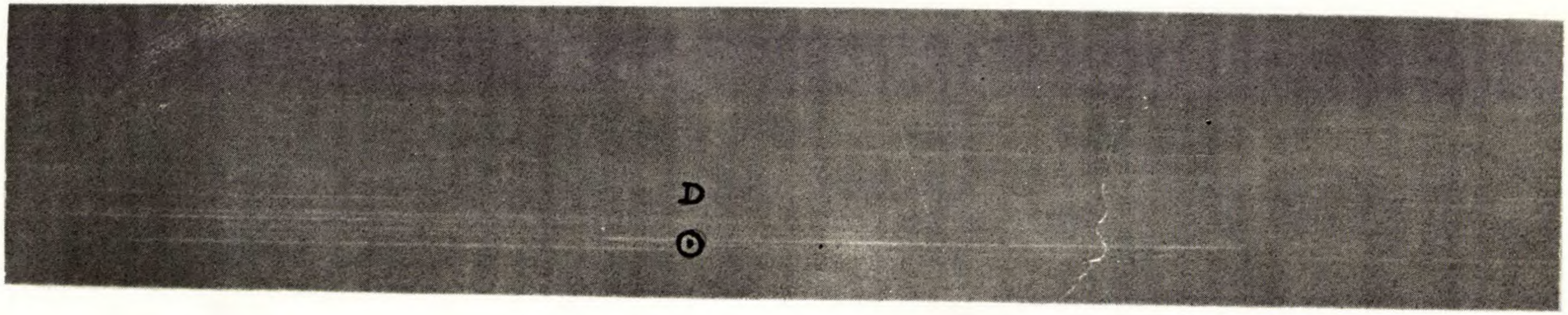


Bottom Billet



Top Billet

Figure 4. Autoradiographic prints of longitudinal billet sections from Ingot 4. Drillings for uranium analysis were taken from points indicated A and B, The results were:- A = 0.082% U; B = 0.082% U. Exposure: 48 hr.



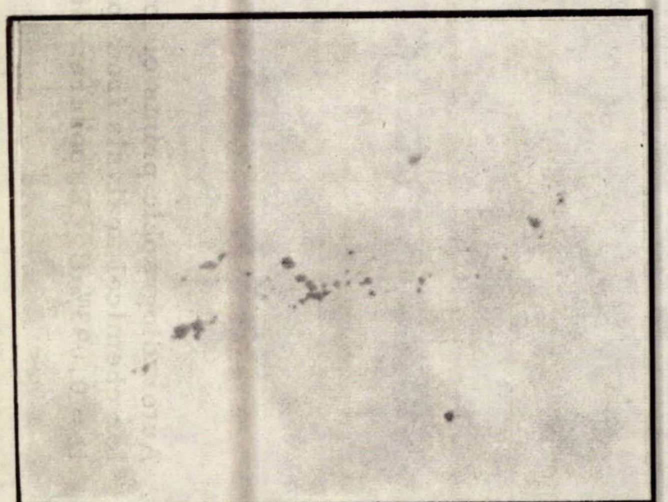
Bottom Billet

Top Billet

Figure 5. Autoradiographic prints of longitudinal billet sections from Ingot 5. Drillings were taken for chemical analysis from points marked C and D. The results were:- C = 0.084%; D = 0.093% U. Exposure: 48 hr.

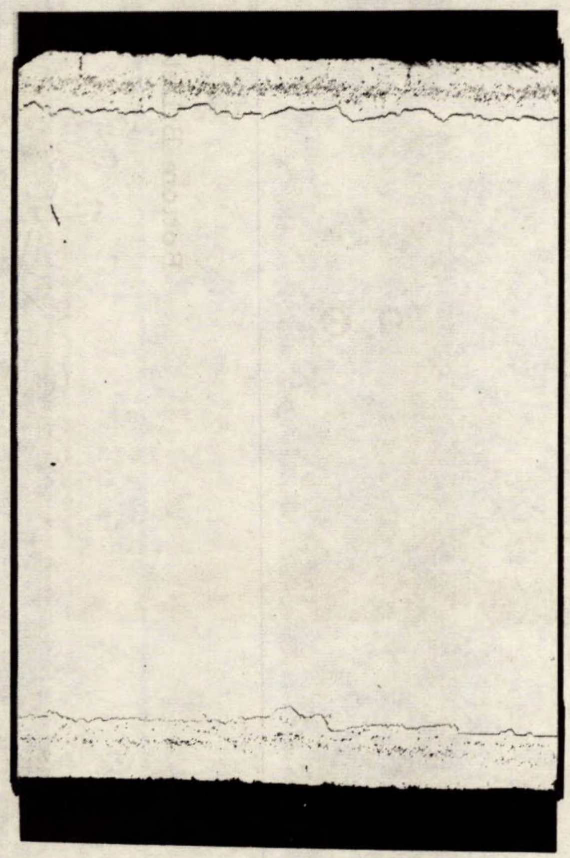
METALLOGRAPHIC EXAMINATION

Samples for metallographic examination were obtained from the bottom billet of uranium-bearing Ingot 4 and from the 0.064 in. diameter RAL (uranium-free) and RALU (uranium-bearing) patented and galvanized wires. The appearance of the clusters of uranium-rich inclusions in the billet sample is illustrated by Figure 6. Figures 7, 8 and 9 illustrate the appearance of the galvanized coating on the RAL and RALU wires. Elongated uranium-rich inclusions can be seen in Figure 8.



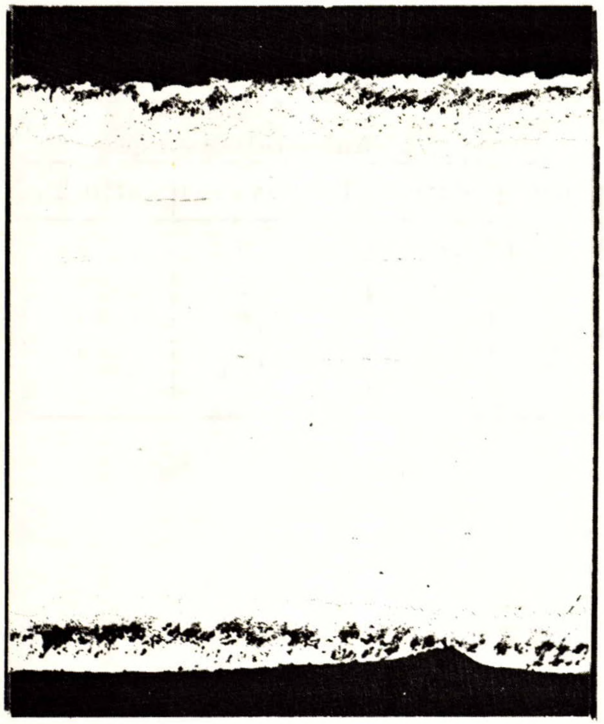
X500, As-polished

Figure 6. Cluster of uranium-rich inclusions in bottom billet of Ingot 4.



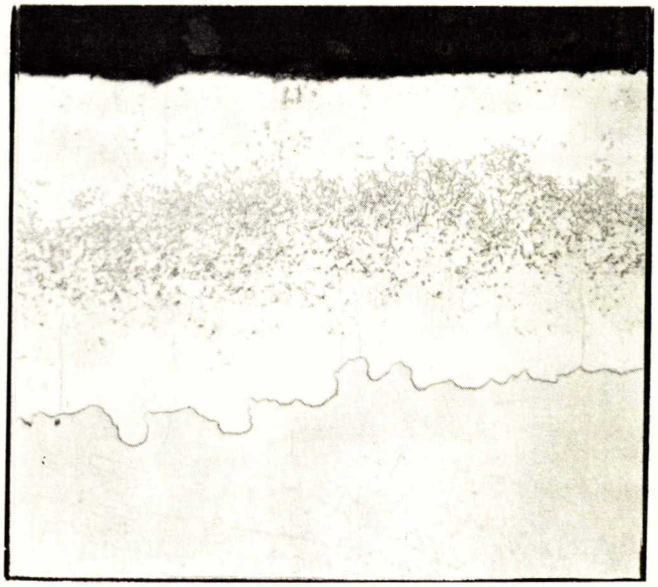
X100, As-polished

Figure 7. Unetched section through 0.064 in. RAL wire showing galvanized coating



X100, As-polished

Figure 8. Unetched section through 0.064 in. RALU wire showing galvanized coating and uranium-rich inclusions.



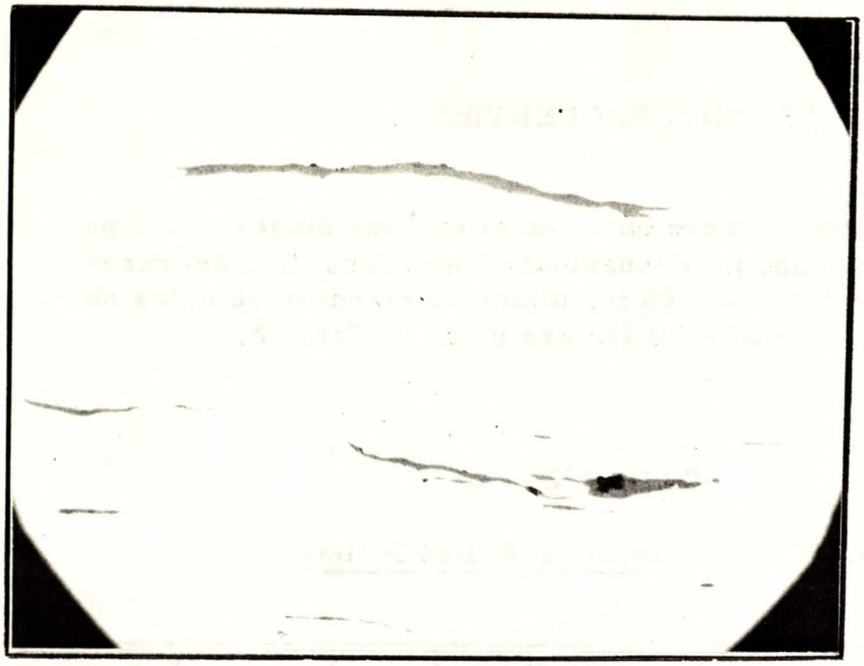
X100, Etched in 2% nital

Figure 9. Structure of galvanized coating on RALU wire.

It will be seen from Figure 10 that the addition of uranium significantly changes the morphology of the sulphide inclusions. A similar observation was also recorded previously (2) with respect to resulphurized stainless steels. It is clear from Figure 10 that in the presence of uranium the sulphides occur as multiple blocky inclusions rather than the malleable stringer type.

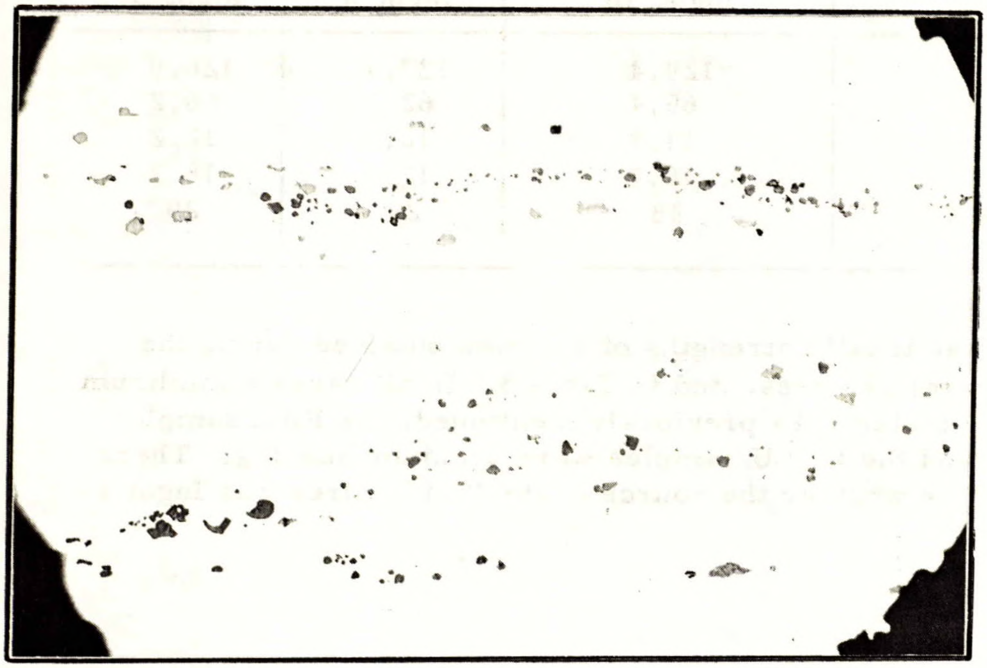
It could be speculated that this change in the characteristics of the sulphide inclusions might result in improved machinability, and tensile ductility in the transverse direction. However, in this case, the transverse to longitudinal ductility ratios appear to be impaired by the presence of uranium, as indicated by the following averages of four tests, using Hounsfield micro specimens prepared from as-rolled 1-3/4 in. square billets.

	Uranium-Free			Uranium-Bearing		
Property	Longitudinal	Transverse	Ratio T/L	Longitudinal	Transverse	Ratio T/L
UTS, kpsi	131.8	125.4	0.95	122.6	121.5	0.99
YS, kpsi	77.8	73.4	0.94	65.9	68.3	1.05
% El	13.7	10.7	0.78	13.7	7.0	0.51
% RA	18.0	9.0	0.50	17.5	6.0	0.34



Uranium-free

C = 0.73%
Mn = 0.63%
S = 0.027%



Uranium-bearing

C = 0.76%
Mn = 0.62%
S = 0.026 %
U = 0.081 %

Figure 10. Photomicrographs of unetched broken fatigue bars of the uranium-free and uranium-treated steels. These bars were machined from as-rolled, 1-3/4 in. square billets representing the bottom of the ingot. Light grey inclusions are manganese sulphide type, and the dark grey ones are oxide type. Some of the light grey inclusions in the uranium-treated steel may be uranium-bearing complex sulphide and the dark inclusions are believed to be uranium oxide. X500, As-polished.

TENSILE PROPERTIES

Numerous samples were obtained at various stages of the processing for the determination of mechanical properties. The average tensile properties of duplicate 0.505 in. diameter standard samples obtained from the 1-3/4 in. square billets are given in Table 2.

TABLE 2

Tensile Properties of as-Rolled Billets

Property	Uranium-Free	Uranium-Bearing	
	Ingot 18	Ingot 4	Ingot 5
UTS, kpsi	129.4	127.1	126.9
0.2% offset YS, kpsi	65.4	62.3	66.2
% El in 2 in.	11.7	12.9	12.2
% RA	16.7	17.3	16.2
Hardness, Rockwell C	28	29	29

The average tensile strengths of samples obtained during the manufacture of the wire are presented in Table 3. In all cases a minimum of two samples were tested. As previously mentioned, the RAL samples were uranium-free and the RALU samples were uranium-bearing. There was no attempt to show whether the source of the RALU wires was Ingot 4 or Ingot 5.

TABLE 3

Tensile Strength (kpsi)* of Material From Various Stages of the Wire Drawing Process

5 Gauge Rod - As Rolled		0.125 in. Wire - As Drawn		0.125 in. Wire - Patented	
RAL	RALU	RAL	RALU	RAL	RALU
131.1	137.0	215.5	214.3	151.7	154.6

BASE WIRE - AS DRAWN

0.051 in.		0.054 in.		0.061 in.		0.064 in.	
RAL	RALU	RAL	RALU	RAL	RALU	RAL	RALU
261.3	260.9	249.0	248.8	236.4	238.0	233.9	233.9

BASE WIRE - AS PATENTED

0.051 in.		0.054 in.		0.061 in.		0.064 in.	
RAL	RALU	RAL	RALU	RAL	RALU	RAL	RALU
173.5	177.8	171.2	175.9	167.7	170.4	166.4	168.2

FINISHED WIRE - AS DRAWN

0.016 in.		0.017 in.		0.019 in.		0.020 in.	
RAL	RALU	RAL	RALU	RAL	RALU	RAL	RALU
321.8	327.5	303.9	303.2	313.2	321.4	314.7	316.4

* DOSCO'S Results

The specified tensile strengths of the finished wires were as follows:

Wire Size, in.	Tensile Strength (kpsi)	
	Maximum	Minimum
0.016	363.5	300.8
0.017	360.0	298.2
0.019	353.5	293.0
0.020	350.0	290.0

The tensile properties of the finished wires were within the specified limits. No significant differences were apparent between the uranium-bearing and uranium-free steels.

Further tensile tests were carried out to determine whether or not the uranium addition had resulted in a change in response to ageing. Table 4 shows the tensile and yield strengths of samples of 0.020 in. cold drawn wire that had been subjected to 5, 10, and 15 minute ageing treatments at 200, 300, 350, 400, 450, 500, 600, and 700°F. The results are shown graphically in Figure 11. Table 5 lists the tensile strengths of 0.020 in. cold drawn wire and 0.064 in. patented and galvanized wire, which had been subjected to ageing treatments at 212 and 400°F for periods of 1/2, 1, 2, 4 and 8 hours.

The ageing behaviour of these materials was similar to that reported for similar steels. No significant differences were apparent between uranium-free and uranium-bearing materials.

TABLE 4

Effect of Ageing on Tensile Properties*
(0.020 in. Diameter Cold Drawn Wire)

Ageing Temp., °F	Uranium-free (RAL) Ageing Time, min						Uranium-bearing (RALU) Ageing Time, min					
	5		10		15		5		10		15	
	UTS (kpsi)	0.2% offset YS (kpsi)	UTS (kpsi)	0.2% offset YS (kpsi)	UTS (kpsi)	0.2% offset YS (kpsi)	UTS (kpsi)	0.2% offset YS (kpsi)	UTS (kpsi)	0.2% offset YS (kpsi)	UTS (kpsi)	0.2% offset YS (kpsi)
200	309.6	243.8	307.7	239.3	310.0	235.4	309.7	242.4	308.7	247.0	310.7	253.0
300	312.9	265.2	317.7	245.0	310.5	253.0	310.2	247.0	310.5	237.8	314.0	237.7
350	315.0	257.5	317.0	248.4	317.5	265.0	314.5	248.4	316.0	253.0	315.0	244.0
400	314.9	252.9	311.1	243.8	313.0	262.1	313.9	263.0	312.6	240.9	313.9	247.0
450	317.3	260.5	313.5	263.7	313.5	254.5	311.5	254.5	309.4	242.5	306.9	242.5
500	298.1	257.5	301.8	251.5	292.7	241.0	303.0	242.2	299.6	251.5	295.1	234.9
600	290.4	254.5	287.0	256.0	286.4	250.0	286.7	254.1	282.6	246.8	281.8	236.2
700	277.3	227.3	274.3	221.2	274.9	232.0	273.0	225.0	271.3	219.8	270.6	224.9

* - Averages of duplicate tests on 0.02 in. diameter cold drawn wire. The unaged samples tested by DOSCO soon after drawing gave the following tensile strengths: RAL - 314.7 kpsi; RALU - 316.4 kpsi.

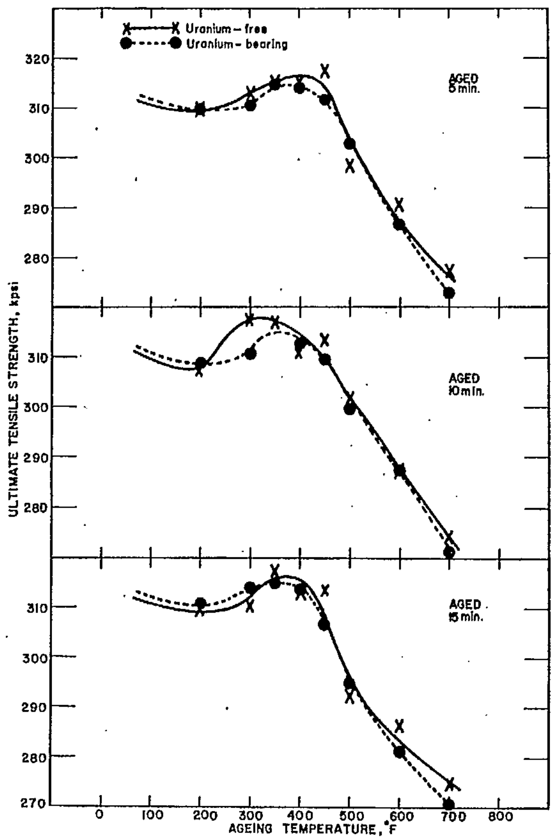


Figure 11. Effect of ageing on the tensile properties of 0.75% carbon steel with and without uranium.
(Tensile strengths of unaged samples were: uranium-free 314.7 kpsi; uranium-bearing 316.4 kpsi).

TABLE 5

Effect of Ageing at 212°F and 400°F on the Room Temperature Tensile Strength of 0.064 and 0.020 in. Wires*

Ageing Time, hr	0.064 in. Patented and Gal. Wire				0.020 in. Cold Drawn Wire			
	RAL		RALU		RAL		RALU	
	212°F	400°F	212°F	400°F	212°F	400°F	212°F	400°F
	UTS (kpsi)	UTS (kpsi)	UTS (kpsi)	UTS (kpsi)	UTS (kpsi)	UTS (kpsi)	UTS (kpsi)	UTS (kpsi)
(Unaged)	(166.4)	(166.4)	(168.2)	(168.2)	(314.7)	(314.7)	(316.4)	(316.4)
1/2	157.0	157.9	157.7	158.1	311.4	310.7	314.2	333.3
1	156.3	156.8	157.8	156.4	313.9	311.1	313.4	307.8
2	155.5	156.2	157.4	157.0	301.3	310.4	310.4	312.7
4	156.6	157.4	157.4	155.1	303.9	308.6	317.2	314.9
8	154.3	156.6	155.2	151.4	292.0	309.6	311.4	321.0

* - Average of duplicate tests except for 1, 2, 8 hr at 212°F for 0.064 in. wire. (Heat treated at the Mines Branch and tested by DOSCO).

TORSIONAL PROPERTIES

Samples of the as-drawn base wires and of the finished wires were tested to failure in torsion at 60 turns per minute in accordance with the wire rope manufacturer's Specification 121-77000. The results are shown in Table 6. The effect of ageing 0.020in. as-drawn wire and 0.064 in. patented and galvanized wire at 400°F and 212°F for periods of 1/2, 1, 2, 4 and 8 hours is shown in Table 7.

The torsional properties were all within the specified limits. No significant differences were observed between uranium-free and uranium-bearing steels.

TABLE 6

Results of Torsion Tests on Wire Samples*
(Turns to failure - Torsion in 8 in.)

Base Wire As-Drawn

0.051 in.		0.054 in.		0.061 in.		0.064 in.	
RAL	RALU	RAL	RALU	RAL	RALU	RAL	RALU
59	61	57	61.5	54	51.5	50	52

Finished Wire

0.016 in.		0.017 in.		0.019 in.		0.020 in.	
RAL	RALU	RAL	RALU	RAL	RALU	RAL	RALU
197.5	199.5	204	203	158.5	167.5	162	149.5
146 min. specified		137 min. specified		123 min. specified		116 min. specified	

* - Average of duplicate "front and back" samples as reported by DOSCO.

TABLE 7

Results of Torsion Tests on Aged Samples of 0.020 in. As Drawn and 0.064 in. Patented Wires*
(Turns to failure - Torsion in 8 in.)

Ageing Time, hr	0.020 in. As-drawn				0.064 in. Patented			
	212°F		400°F		212°F		400°F	
	RAL	RALU	RAL	RALU	RAL	RALU	RAL	RALU
(Unaged)	(162)	(149.5)	(162)	(149.5)	-	-	-	-
1/2	153.5	142.5	151	153.5	21	18.5	20	22
1	157	154	157	151.5	20	21	18.5	19.5
2	162	146.5	149	159	21	18.5	17	13.5
4	158.5	147	155.5	162.5	20	19	21	18
8	153.5	154.5	155.5	160	24	23	20.5	18

* - Averages for duplicate samples. (Heat treated at Mines Branch and tested by DOSCO.

FATIGUE PROPERTIES

Notched and unnotched fatigue bars were tested in R. R. Moore machines (10,000 rpm type). The tests were carried out (3) in both the air and mildly corrosive environments. The results are listed in Tables 8, 9, and 10, and shown graphically in Figures 12 and 13.

Samples machined from the bottom billets of the uranium-bearing steel appeared to exhibit a lower fatigue limit than samples from the top and middle billets (Table 8, Figure 12). The latter materials had a fatigue limit of 50,500 psi, the identical value to that obtained for the uranium-free steel. The fact that material from the bottom of the uranium-bearing ingots exhibited a fatigue limit of only 48,000 psi is indicative of a possible deterioration of fatigue properties in zones of increased concentration of uranium-rich inclusions. This value would have to be considered the true fatigue limit for the uranium-bearing steel. The fatigue ratios of 0.39 for the uranium-free steel and 0.38 for the uranium-bearing steel appear to be low, but are, nevertheless, identical to published values for normalized AISI 1080 steel (4).

The notched fatigue limits of the uranium-free and uranium-bearing steels were 34,500 psi and 30,500 psi, respectively, (Table 9, Figure 12). The fatigue strength reduction factors (Kf) were 1.46 and 1.57. Assuming 3 as the theoretical stress concentration factor, Kt, the notch-sensitivity index q*, of the uranium-free and uranium-bearing steels are 0.230 and 0.285, respectively. This difference implies that the uranium-treated steel is more notch sensitive than uranium-free material. The increased notch sensitivity could be attributed to the presence of more inclusions in the uranium-bearing steel (Figures 6 and 10).

Corrosion fatigue tests (Table 10, Figure 13) carried out on unnotched R. R. Moore specimens in a tap water environment at 8000 rpm indicated that the uranium-bearing steel was slightly inferior. This is shown in Figure 13, which indicates that the corrosion endurance limits of 10^6 cycles were 45,000 psi for the uranium-free steel and 42,500 psi for the uranium-bearing steel. It is significant that these values are of the same order as those reported by Brown (4) for normalized AISI 1080 steel.

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* The notch sensitivity (5,6) of a material in fatigue is usually expressed by a notch sensitivity index q as follows: $q = \frac{Kf-1}{Kt-1}$

where Kf = fatigue strength reduction factor, i.e. $\frac{\text{fatigue limit unnotched}}{\text{fatigue limit notched}}$

and Kt = geometric (theoretical) stress concentration factor, since it is a function only of the geometry of the notch.

TABLE 8

Results of Fatigue Tests on Unnotched R.R. Moore Specimens
Machined From As-Rolled 1-3/4 in. Square Billet Stock

Applied Stress psi	Uranium-Free		Uranium-Bearing			
			Samples from bottom		Samples from top and middle	
	No. of Cycles	Remarks	No. of Cycles	Remarks	No. of Cycles	Remarks
40,000	-	-	-	-	13,182,000	UB
43,000	-	-	-	-	12,870,000	UB
44,000	14,618,000	UB*	14,912,000 11,726,000	UB UB	-	-
45,000	13,484,000	UB	11,697,000 10,720,000	UB UB	1,154,000	B
46,000	-	-	-	-	13,534,000	UB
48,000	12,883,000	UB	13,752,000 1,105,000	UB B	13,668,000	UB
49,000	14,793,000	UB	888,000	B	13,423,000	UB
50,000	13,905,000 12,647,000 958,000	UB UB B**	683,000 624,000 479,000 239,000	B B B B	13,961,000 13,232,000	UB UB
51,000	17,427,000 428,000	UB B	10,981,000 10,752,000 411,000	UB UB B	11,945,000 994,000	UB B
52,000	564,000	B	-	-	399,000 209,000 351,000	B B B
53,000	417,000	B	718,000 469,000	B B	421,000	B
55,000	-	-	-	-	718,000	B
60,000	-	-	-	-	63,000	B
65,000	66,000	B	25,000	B	-	-

* UB - Unbroken; ** B - Broken

TABLE 9

Results of Fatigue Tests on Notched R.R. Moore Specimens Machined From As-Rolled 1-3/4 in. Square Billet Stock

Applied Stress psi	Uranium-Free		Uranium-Bearing	
	No. of Cycles	Remarks	No. of Cycles	Remarks
20,000	13,040,000	UB*	-	-
23,000	15,371,000	UB	-	-
25,000	14,670,000	UB	-	-
27,000	16,286,000	UB	-	-
28,000	-	-	12,537,000	UB
30,000	16,054,000	UB	14,150,000	UB
31,000	-	-	477,000	B
32,000	14,978,000	UB	427,000	B
34,000	15,799,000	UB	266,000	B
35,000	1,145,000	B**	-	-
36,000	859,000	B	1,460,000	B
38,000	650,000	B	161,000	B

* UB - Unbroken; ** B - Broken

TABLE 10

Results of Corrosion Fatigue Tests on Unnotched R.R. Moore Specimens Machined From As-Rolled 1-3/4 in. Square Billet Stock

(Tested in Tap Water - 8000 rpm)

Applied Stress psi	Number of Cycles to Failure	
	Uranium-Free	Uranium-Bearing
36,000	2,765,000	3,738,000
38,000	4,986,000	2,393,000
	4,549,000	1,940,000
40,000	9,401,000	2,284,000
	2,032,000	2,093,000
	5,151,000	820,000
45,000	940,000	792,000
50,000	556,000	448,000

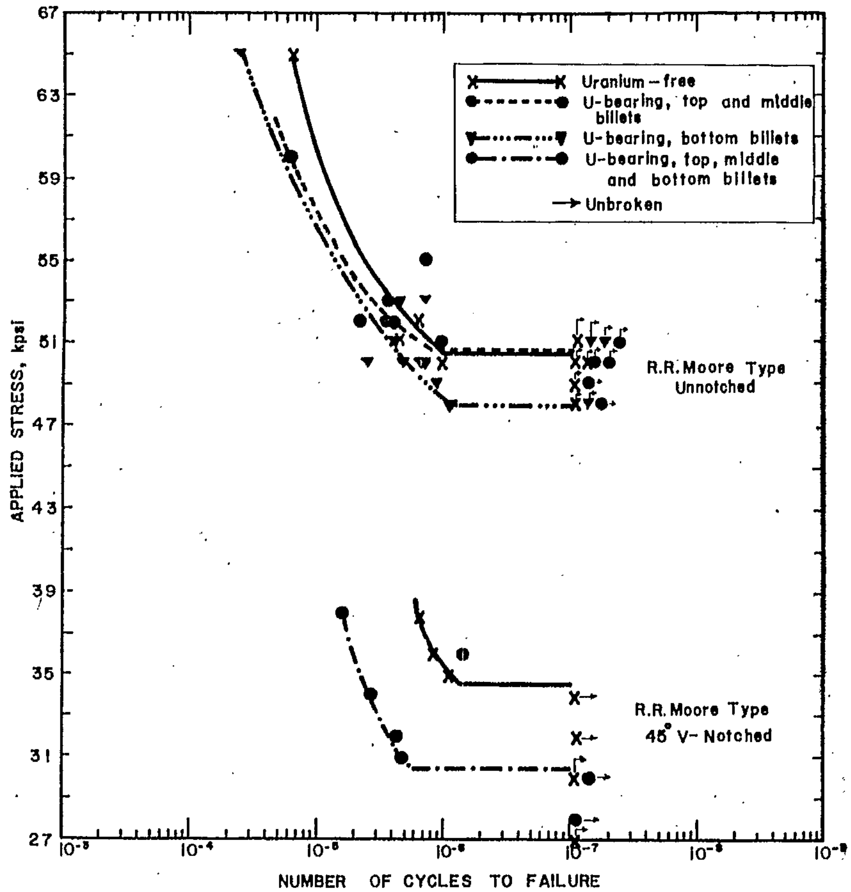

Figure 12. Rotating-beam fatigue characteristics of 0.75% carbon steel with and without uranium. (Test bars were prepared from hot-rolled 1-3/4 in. square billets).

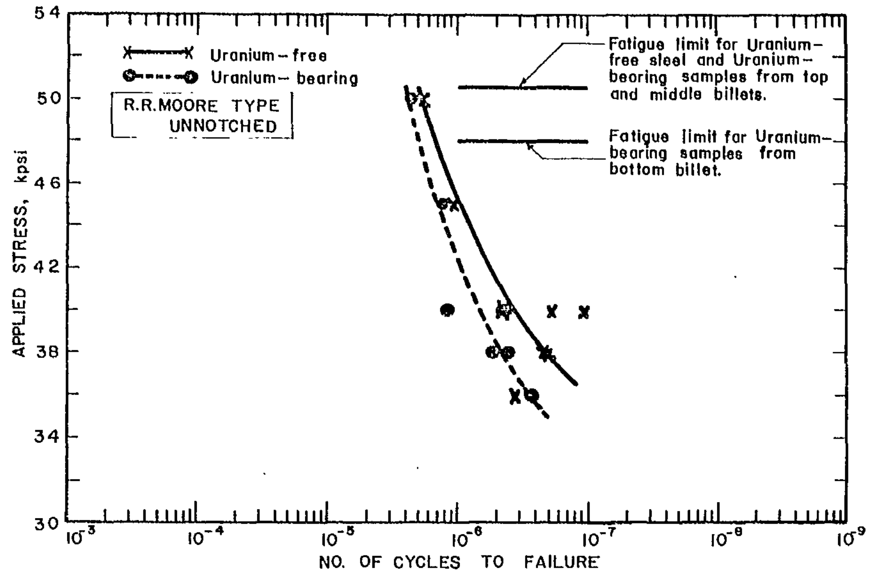

Figure 13. Rotating-beam corrosion fatigue characteristics of 0.75% carbon steel with and without uranium. (Test bars were prepared from hot-rolled 1-3/4 in. square billets).

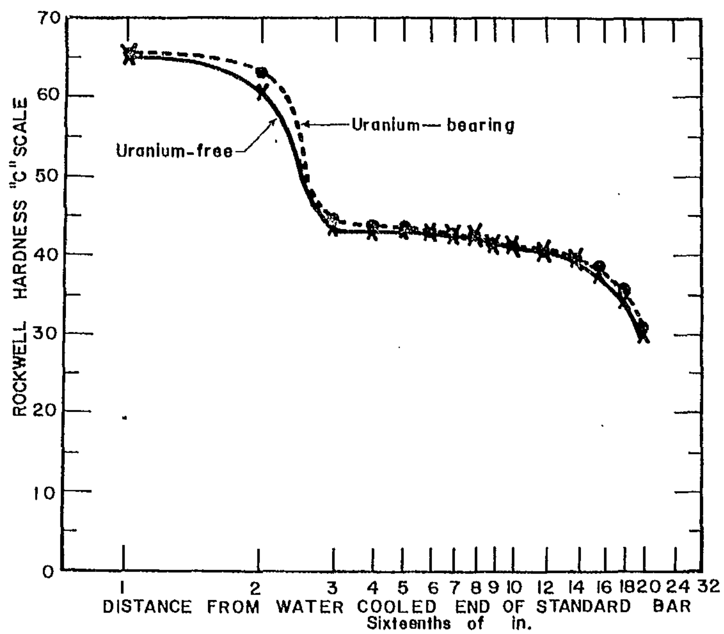

Figure 14. End-quench hardenability test data.

OTHER PROPERTIES

Other miscellaneous tests showed no significant differences between uranium-free and uranium-bearing samples, but the results are presented here for purpose of record.

The Charpy V-notch impact strength of the as-rolled, uranium-free billet material was 5.5 ft-lb (average of 6 tests). The corresponding value for the uranium-bearing steel was 6.8 ft-lb (average of 12 tests).

There was no significant difference in the hardness of the uranium-bearing and uranium-free wires. The Knoop hardness of the 0.064 in. patented and galvanized wire was 408 (R_c 41), and that of the 0.020 in. cold drawn wire was 542 (R_c 50).

The average results of end-quench Jominy hardenability tests carried out on samples machined from the as-rolled billets are shown in Figure 14, page 27.

PROPERTIES OF WIRE ROPE

The weight of each wire size required for 1000 ft of rope was reported by the wire rope manufacturer as follows:

Size, in.	Approx. wt, lb
0.020	1.4
0.019	23.0
0.017	6.0
0.016	100.0
Total	130.4

The finished rope was subjected to fatigue endurance testing as outlined in U. S. Military Specification No. MIL-W-115A. Experimental 1000 ft lengths of "1/4 in. 7 X 19 Aircord" were prepared from RAL and RALU wires using the standard procedures for this class of materials. The "aggregate strengths", that is, the total breaking loads of the individual wires comprising the cord, were: RAL = 8990 lb; RALU = 9130 lb (wire rope manufacturer's results). The breaking strength of the cords was determined (a) as manufactured, (b) after 130,000 reversals as required by Specification MIL-W-115A, and (c) after 195,000 reversals. The average results are recorded in Table 11.

The fabrication of the wire resulted in a loss in tensile strength of 19% for the RAL and 18% for the RALU material as compared with the "aggregate strengths". Losses up to 25% are reported to be commonplace.

On the basis of the small number of samples tested, it is apparent that the uranium-bearing steel exhibits a greater loss of tensile strength after endurance testing than does the uranium-free steel. However, the experimental scatter was too large to make any firm conclusions.

TABLE 11

Average Results of Breaking Strength Tests on Experimental Cord*

Condition	RAL			RALU		
	Breaking Strength lb	Experimental Scatter lb	No. of Tests	Breaking Strength lb	Experimental Scatter lb	No. of Tests
"Aggregate strengths"	8990	-	-	9130	-	-
As manufactured	7280	270	6	7469	100	6
After 130,000 reversals - at top pulley	6815	690	2	6643	35	2
After 130,000 reversals - at bottom pulley	6328	195	2	5980	510	2
After 195,000 reversals - at top pulley	6306	315	2	6685	250	2
After 195,000 reversals - at bottom pulley	6068	715	2	5210	1460	2

* - Test results from wire rope manufacturer

CONCLUSIONS

1. The recovery of uranium when added to the commercially produced fully-killed high carbon steel ingots, was slightly above 70%.

2. The distribution of uranium as determined by chemical analysis, in the semi-finished and finished products was uniform for all practical purposes.

3. It was apparent from the autoradiographs of the longitudinal billet sections that some segregation towards the bottom of the ingot had occurred.

4. The addition of uranium resulted in a noticeable increase in inclusion content.

5. The effect of uranium on the morphology of sulphides was significant. The presence of uranium favoured the occurrence of multiple blocky sulphides rather than long stringer type.

6. The addition of uranium up to about 0.1% to 0.75% carbon steel was neither detrimental nor beneficial with respect to:

   (a) tensile properties at various stages of the processing,
   (b) torsion characteristics at various stages of the processing,
   (c) room temperature Charpy V-notch impact properties,
   (d) hardness,
   (e) end-quench (Jominy) hardenability,
   (f) response to ageing treatments.

7. The addition of uranium resulted in slight decreases in the fatigue limit, notched fatigue limit, and corrosion fatigue limit.

8. The addition of uranium increased the notch sensitivity of the steel.

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