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OTTAWA May 12th, 1942.

REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 1218.

Examination of Cast Tungsten Carbide.

(Copy No. 14.)

BUREAU OF MINES
DIVISION OF METALLIC MINERALS

ORE DRESSING AND
METALLURGICAL LABORATORIES

CANADA
DEPARTMENT
OF
MINES AND RESOURCES
MINES AND GEOLOGY BRANCH

OTTAWA May 12th, 1942.

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Object of Report:

To study the properties of cast tungsten-carbide cores made to the .303" W.M.K. 1 - A.P. core dimensions and design.

Origin of Material:

The cast tungsten carbide used in this work was sent in on March 14th, 1942, by Mr. Howard Biers, of the Electro Metallurgical Co. of Canada Limited, Welland, Ontario. Thirty-one (31) cylindrical tensile test pieces, ¼ inch in

(Origin of Material, cont'd) -

diameter and 1½ inches long, and thirty-three (33) .303" calibre bullet cores were submitted for examination.

Dimensions:

The specified dimensions of the .303 W.M.K. 1 A.P. core are given in Figure 1. The cast tungsten-carbide cores were within the following dimensions:

Diameter: 0.250 ± 1 inch
Length: 1.125 ± .005 inch
Radius of curvature: 1.0 inch

Surface imperfections were corrected by a nickel plating (detected by spectrographic analysis of the surface).

Average volume (as found from water displacement): 0.753_6 c.c.

Some variation in the volume was observed, some cores having a more or less sharp nose point (see Figure 2).

Weight:

Average of 9 cores - 169.2 grains.
(Low, 168.6 grains; high, 170.3 grains).

Density:

Cores: (average of three) -- 14.56_9

Test pieces: -- 14.65_6

MECHANICAL TESTS:

Hardness -

The hardness was taken by the Vickers method (using a 50-kilogram load) both on a section cut perpendicularly and on one cut parallel to the long axis of the core.

(a) On a cross-section: Centre of core - 776-802 V.H.N.
1 mm. from edge - 902 "
½ mm. " " - 1118 "
(b) On longitudinal section (about 1 mm. from edge): - - - 1044 V.H.N.

Surface hardness (beneath nickel plating): - 1260 V.H.N.

(Continued on next page)

(Mechanical Tests, cont'd) -

Hammer Test -

The hammer test consists in measuring the energy required to break the bullet core lying between two small flat anvils; the breaking load is applied perpendicularly to the long axis by means of a moving steel rod on which a known weight (890 grams) is falling in air from various heights. No correction is made for the air resistance.

Sample No.	Falling distance of weight (890 grams)	Remarks	Energy Gram-centimetre	Energy Foot-pounds
1.	40 cm.	No break.	35,600	2.57
2.	No. 1, repeat	No break.	35,600	2.57
3.	No. 1, 45 cm.	Break (three fragments - see Figure 7a).	40,000	2.89
4.	60 cm.	Break (several small fragments - see Figure 7b).	53,400	3.86
5.	50 cm.	Break.	44,500	3.21
6.	45 cm.	Break.	40,000	2.89

Compression Test -

Description of test piece: cylindrical, 0.50 in. long by 0.25 in. in diameter.

Rate of loading: 600 pounds per minute.

(Continued on next page)

(Mechanical Tests, cont'd) -

(Compression Test, cont'd) -

Sample No.	Compression, in pounds	P.s.i.
1.	16,880	344,000
2.	14,150	288,000
3.	13,620	277,000
4.	16,450	335,000
5.	13,820	282,000
6.	14,400	294,000
Average:	14,886	303,000

Fragmentation: lamellar, small fragments.

Transverse Test -

The test pieces were made from cylinders 0.250 inch in diameter by 1½ inches long. Two symmetrical parallel surfaces were ground 0.200 inch distance apart. These test pieces were broken between 1.15-inch sintered carbide centres, the load being applied in the middle of the pieces at a constant rate of 200 pounds per minute.

Sample No.	Breaking load, in pounds	Modulus of rupture (calculated), p.s.i.
1.	178	34,100
2.	190	36,400
3.	178	34,100
4.	146	28,000
5.	192	36,800
6.	204	39,100
7.	188	36,000
8.	188	36,000
MEAN	183	35,100

Fracture: silvery, metallic.

Spectrographic Analysis:

Essential - W, Co
Very strong trace - Si
Strong traces - Fe, Mn, Ni, Mo
Traces - Cu, Ti
Nil - Ta

Chemical Analysis:

		Per cent
Tungsten	-	83.52
Carbon	-	4.70
Cobalt	-	10.02
Silicon	-	0.30
Iron	-	1.29
Nickel	-	None detected.
		99.83

Microscopical Examination:

Sections were taken perpendicular and parallel to the long axis of the cast tungsten carbide cores and given a metallographic polish by means of diamond powder. As seen in Appendix A, the following points were observed:

(a) Large cavities of the order of 200 μ appear in the centre of the core. See Figure 3, magnification X40, unetched.

(b) There is considerable enrichment of the cobalt-tungsten carbide phase at the centre of the core (Segregation). See Figures 4, 5 and 6.

(c) The tungsten-carbide grains are coarse on the average (200 μ); there is a decrease in the grain size towards the surface of the core 15 to 20 μ. See Figures 4, 5 and 6.

(d) The tungsten-carbide crystals are geometrically well formed with sharp angles.

(e) The tungsten-carbide crystals are fairly well dispersed in the matrix and have but a few points of inter-contact, especially in the centre of the core. See Figures 5 and 6.

SEE APPENDIX A FOR FIGURES.

-

X-Ray Crystallographic Examination:

The structure of the cast tungsten carbide was studied by X-ray diffraction, using the Debye-Scherrer and back radiation methods (see Appendix B). The results of this X-ray analysis revealed:

(a) A random orientation of large crystals (averaging 200µ) in the centre of the core. See Figure 7.

(b) The presence of mono-tungsten carbide, di-tungsten carbide, and some metal tungsten crystals. See Figures 8 to 16, Appendix B.

Bulleting:

The bulleting of the cast tungsten-carbide cores was done at the Dominion Arsenal, Quebec City, Quebec. Considerable trouble was experienced during the bulleting due to the breakage of the cores inside the lead sleeve when closing the gilding-metal-coated steel jacket (as shown in Figure 17, Appendix C); of the twenty-five cores in hand at the beginning, only thirteen remained intact at the end of the operation.

Discussion of Results:

Dimensions -

The dimensions of the cores were within the specified tolerances. Stress should be placed on this fact in favour of the casting process.

Density -

The variation of the density of cemented tungsten carbide with various cobalt contents is as follows:

Per cent cobalt:	2.5	5.0	7.5	10.0	12.5	15.0
Density:	15.2	14.8	14.6	14.3	14.1	13.8

The high density values recorded on the cast

(Discussion of Results, cont'd) -

Density, cont'd -

tungsten-carbide samples, notwithstanding the cavities present, constitute a first indication of the presence of a higher-density constituent such as the di-tungsten carbide W_2C (density 17.16) or metal tungsten W (density 19.3), which constituents were found in the X-ray analysis.

Influence of the density on core penetration:

Experimental values gathered from various dependable sources seem to indicate that the penetration of a small arms bullet core would be a function of the sectional density to the first power. A higher density should therefore be sought for core material, so long as this increase in density is not brought forth at a sacrifice of other desirable properties.

Hardness -

Influence of core hardness on armour plate penetration:

The exact relation between armour plate penetration and hardness of the core at high velocity is not known. It seems reasonable, however, to assume that for a given plate hardness and thickness there is a limiting value of hardness below which the core will not maintain its rigidity, resulting in additional work performed upon hitting the plate and a consequent loss in penetration.

The hardness observed on the cast tungsten-carbide cores varies from the outside to the inside, where it is lower and of the order of hardness obtainable with alloy steel as read on the Vickers machine (obviously, some areas on the tungsten carbide are relatively much harder than indicated by the Vickers readings which give the average hardness of the high-cobalt tungsten-carbide matrix).

(Continued on next page)

(Discussion of Results, cont'd) -

Strength -

The cast tungsten carbide under examination has a poor resistance to low-velocity blows, an energy of three (3) foot-pounds being sufficient to cause breaking.[@] The modulus of rupture is relatively very low, 35,000 p.s.i.[@@] compared with the 250,000 to 300,000 p.s.i. obtainable with the sintered tungsten carbide of the same cobalt composition. In short, the bullet cores submitted are seen to have comparatively poor strength and toughness in static and low-velocity tests. Although the behaviour of a body is somewhat different at high velocity, it can be predicted that at a velocity approaching 3,000 ft./sec. the rigidity of the cast tungsten carbide will likely not have changed sufficiently to bring about an appreciable increase in the strength of the core.

Composition -

The low carbon content (4.70 per cent) indicates that all of the tungsten is not present as mono-tungsten carbide, for in this case the amount of tungsten present would require a value of 5.46 per cent carbon. Neglecting the carbon present as iron carbide, and assuming no metallic tungsten, 28 per cent of the tungsten should be as di-tungsten carbide in order to fit in with the carbon content found in the cast specimen; however, crystal analysis showed also traces of free tungsten which would lower the above percentage of di-tungsten carbide actually present.

Cobalt -

The effect of cobalt as binder on the hardness is

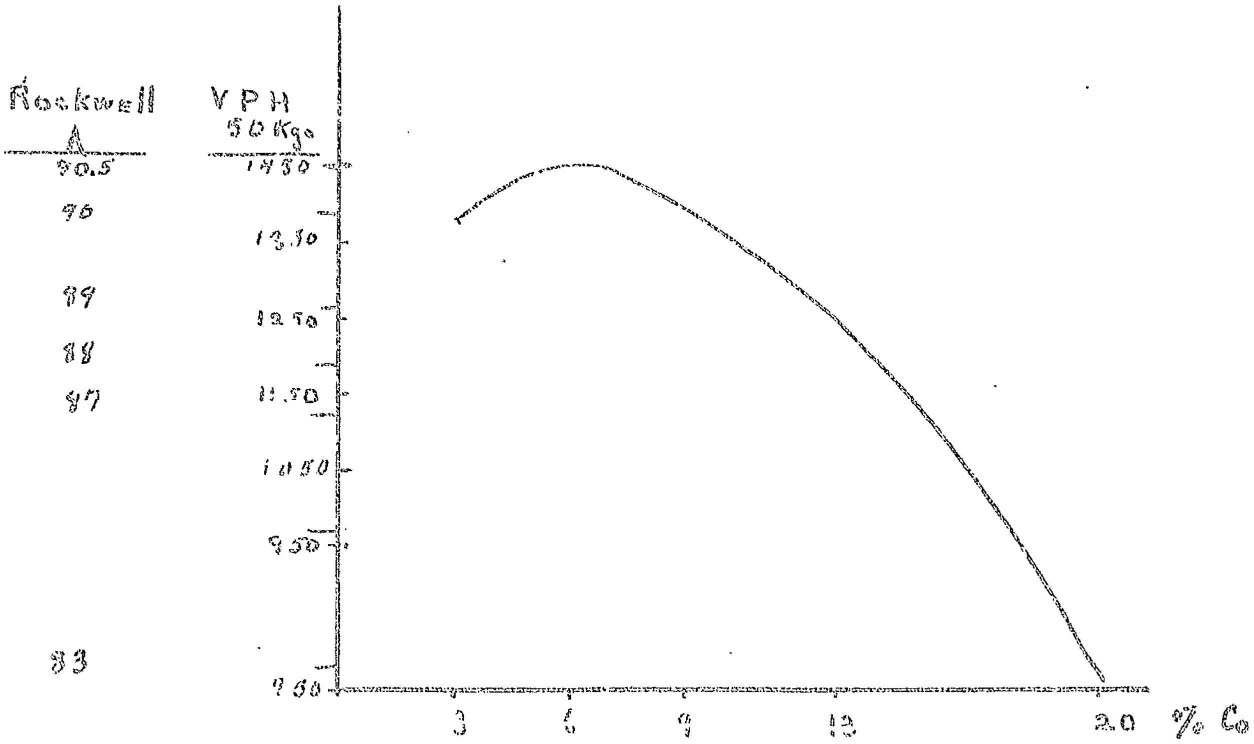
[@] In contrast, at low velocity roughly 20 foot-pounds energy is required to break a sintered tungsten carbide of average toughness.

[@@] This modulus of rupture, however, is a fair value for a cast tungsten carbide.

(Discussion of Results, cont'd) -

Cobalt, cont'd -

shown by the following approximate curve for sintered tungsten carbide, the cobalt content being the only variable, other conditions (grain size, composition, etc.) remaining constant. Approximately the same effect should be expected in the case of a cast product.



Silicon -

It is claimed that the presence of silicon in the sintered cobalt - tungsten carbide will decrease the grain growth. This point, however, is questionable, and silicon when contained originally as silicon oxide (coming from impure

(Discussion of Results, cont'd) -

Silicon, cont'd -

powders) will be detrimental to the strength of the final product. In the cast tungsten carbide, the silicon content can be considered as sufficiently low.

Iron -

Addition of iron to the tungsten carbide will lower the density of the final product. When added in small quantities, it was noted that it increases the toughness of the sintered tungsten carbide.

Microscopical and X-Ray Examination -

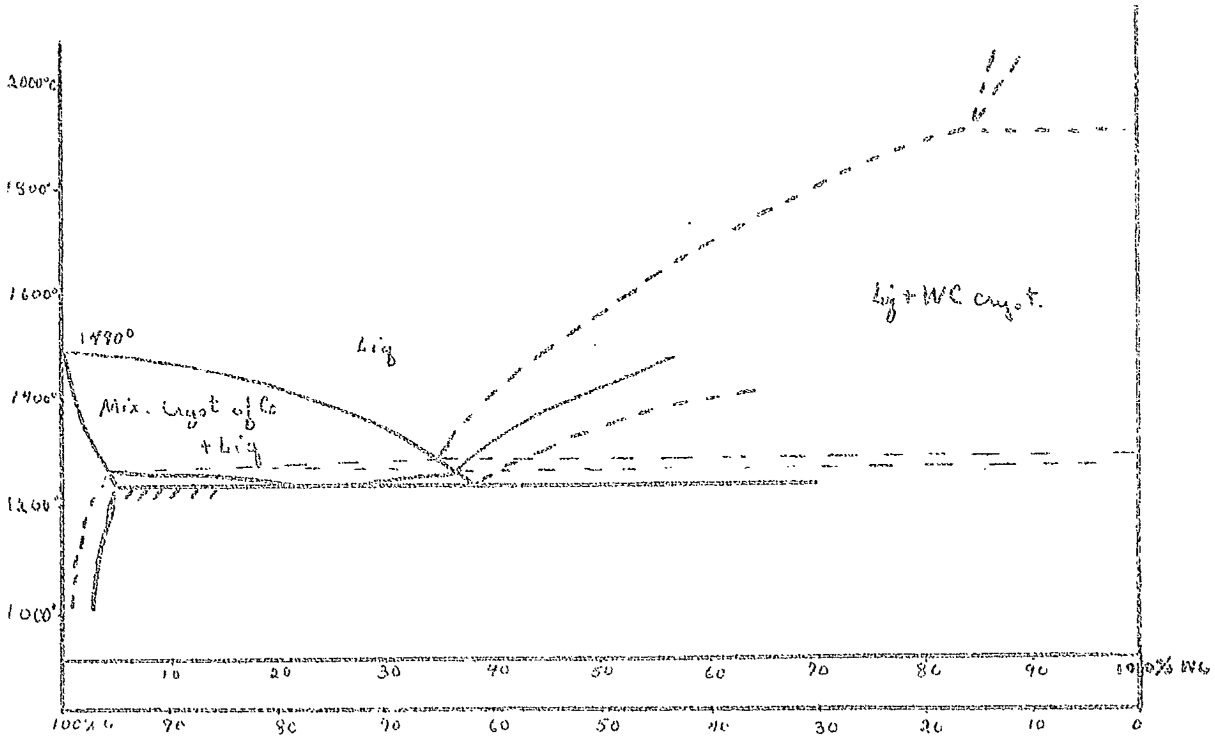
Cavities due to shrinking are detectable in the cast tungsten carbide. These large irregular hollows can be considered harmful when present in a bullet core since they have a tendency to decrease the strength and density of the material.

Both X-ray and microscopical examination have shown the presence of a very coarse structure in the centre of the core, the crystal decreasing in size near the edge. When the cooling from above the liquidus is not rapid enough (chilling), there is a tendency of the cobalt to enrich at the centre of the core, as observed in the cast samples under examination. The material directly in contact with the mould tends to reject tungsten carbide according to the equilibrium diagram given below and form an outer shell of lower cobalt content which will be hard and brittle if the carbide rejection has been excessive.

(Equilibrium diagram is shown on next page)

(Discussion of Results, cont'd) -

Microscopical and X-Ray Examination, cont'd -



Temperature-Composition Equilibrium Diagram of the Cobalt-Tungsten-Carbide System.
(Stäger: Ann. Suisses, 1940)

The cobalt enrichment at the centre would favour the formation of large crystals of tungsten carbide. Furthermore, these secondary crystals under a suitable cooling rate will tend to grow isolated and have but a few points, if any, of inter-contact with the neighbouring crystals. Moreover, their contours will also appear as of very definite, well detached, geometrical shape with sharp angles (see large bright crystals in Figures 5 and 6, Appendix A).

(Continued on next page)

(Discussion of Results, cont'd) -

Microscopical and X-Ray Examination, cont'd. -

Effect of crystal shape, size and segregation on mechanical properties:

Poor strength and poor toughness are generally associated with the sharp angular configuration observed in Figures 5 and 6. The coarse crystal growth will have an appreciable effect on the hardness, lowering it to a considerable extent.® Similarly, a higher cobalt concentrate will contribute in lowering the hardness at the centre. Much higher hardnesses are found on the surface where the crystals are finer and the tungsten carbide - cobalt matrix is relatively poor in cobalt.

The X-ray crystal analysis has shown that the cast sample contains mono- and di-tungsten carbides and also metal tungsten. This might arise from various causes:

(a) Initial content of metal tungsten used along with the cobalt metal binder in the powdered tungsten carbide. Above the liquidus point (see constitution diagram for 10 per cent cobalt) the following reaction would take place:

$$W + WC \rightleftharpoons W_2C$$

(b) During the melting, at a sufficiently high temperature the dissociation of tungsten carbide will become appreciable, as follows:

$$3WC \rightleftharpoons W_2C + W + 2C$$

In the vacuum melt, indications are that at temperatures above 2000° C. the free carbon resulting from the dissociation will start to vapourize slowly, leaving a mixture of $W + W_2C + WC$. In a hydrogen

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® See O. Meyer and W. Eilender, Archiv für das Eisenhüttenwesen, p. 550, 11, 38, for effect of grain size on hardness of sintered tungsten carbide.

Microscopical and X-Ray Examination, cont'd -

atmosphere, if the hydrogen does not contain a sufficient amount of methane⊛ before reaching the molten carbide the following reaction will tend to decrease the carbon content of the tungsten carbide:

$$2WC + 2H_2 \rightleftharpoons CH_4 + W_2C \qquad ⊛⊛$$

and further,

$$W_2C + 2H_2 \rightleftharpoons 2W + CH_4 \qquad ⊛⊛$$

The crystals of di-tungsten carbide (W_2C) are of the same structural type (hexagonal, see Appendix B) as the mono-tungsten carbide and cannot be easily discerned from the mono-tungsten carbide (WC) under the microscope.

Effect of these constituents on the mechanical properties:

Di-tungsten carbide (W_2C) has a higher molecular weight, a higher density (17.2) but a lower atom concentration and a lower hardness⊛⊛⊛ than the mono-tungsten carbide (WC). As calculated by means of Friedrich formula,

$$\text{hardness} = \frac{100 \times \text{Density} \times \text{Valence}}{\text{Molecular Weight}},$$

the hardness of W_2C is only about two-thirds that of WC.

The presence of the di-tungsten carbide and tungsten constituents would therefore probably reduce the hardness of the material. The di-tungsten carbide is considered as more brittle than the mono-tungsten carbide. Its presence would therefore affect the toughness of the cast material. Experimental results⊛⊛⊛ indicate, however, that for sintered tungsten

(Concluded on next page)

⊛ This quantity at 2000° C. is very small! 0.003

⊛⊛ For convenience, the hydrocarbon formed is considered as methane at these high temperatures.

⊛⊛⊛ O. Meyer and W. Eilender, Archiv für das Eisenhüttenwesen, p. 553, 11, 38.

(Discussion of Results, cont'd) -

Microscopical and X-Ray Examination, cont'd -

carbide containing 8 per cent cobalt, addition of tungsten will actually increase slightly the hardness and lower the toughness.

Firing Trials:

Thirteen rounds were fired at the Experimental and Proof Establishment, at Valcartier, Quebec. The results obtained will be reported and sent forward by Col. E. N. Ransford, of the Directorate of Small Arms and Ammunition, Inspection Board of the United Kingdom and Canada, Ottawa.

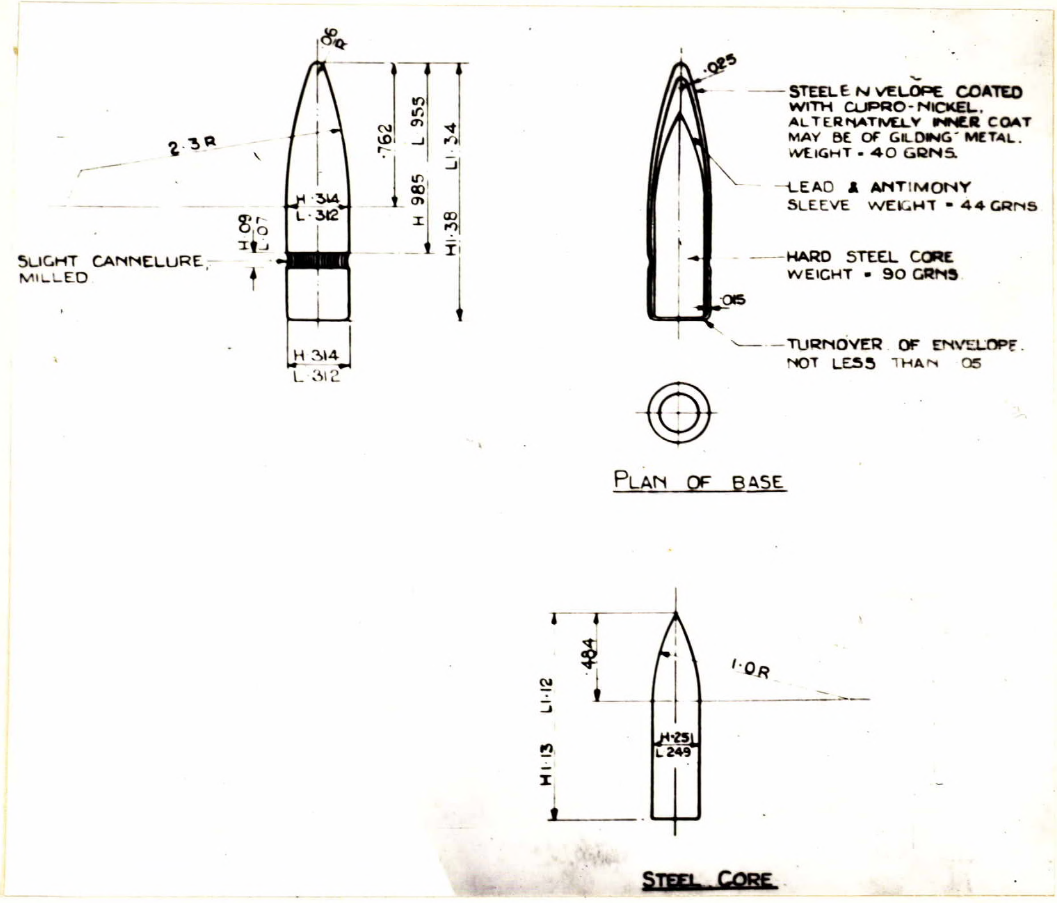
Conclusions:

The examination of some thirty-three (33) cast tungsten carbide .303" bullet cores, submitted by Mr. H. Biers, of the Electro Metallurgical Co. of Canada Limited, Welland, Ontario, shows that the casting process will produce a core of suitable dimensions within the specified tolerances. However, the hardness, modulus of rupture, and especially the resistance to impact at low velocity, are relatively poor compared with those observed on sintered tungsten carbide and would likely result in poor performance against hard plate at higher velocity. It is possible that these mechanical properties can be improved by modifying the composition and developing a suitable heat treatment of the cast product.

Ottawa, May 15th, 1942.
RP:PES.

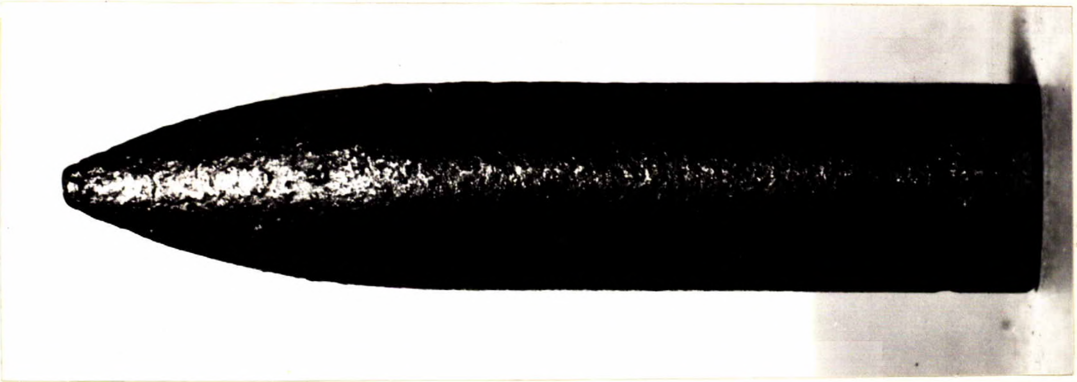
APPENDIX A. - Micro and Macro Figures.

Figure 1.



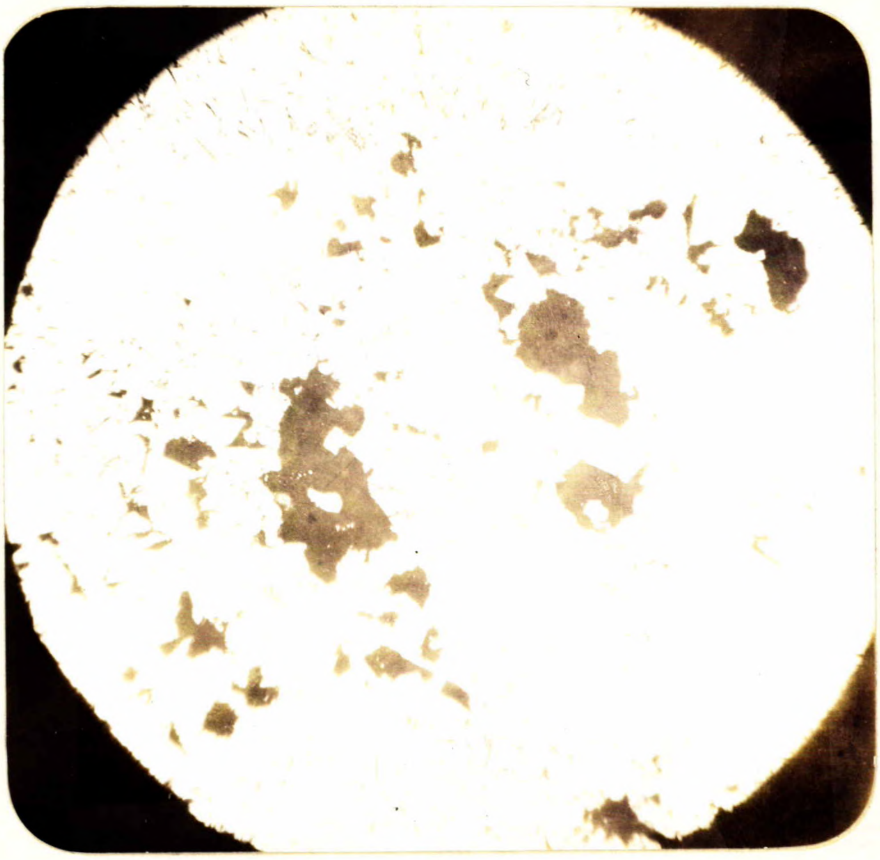
Drawing of the .303" A. P. bullet.
(Approximately to size).

Figure 2.



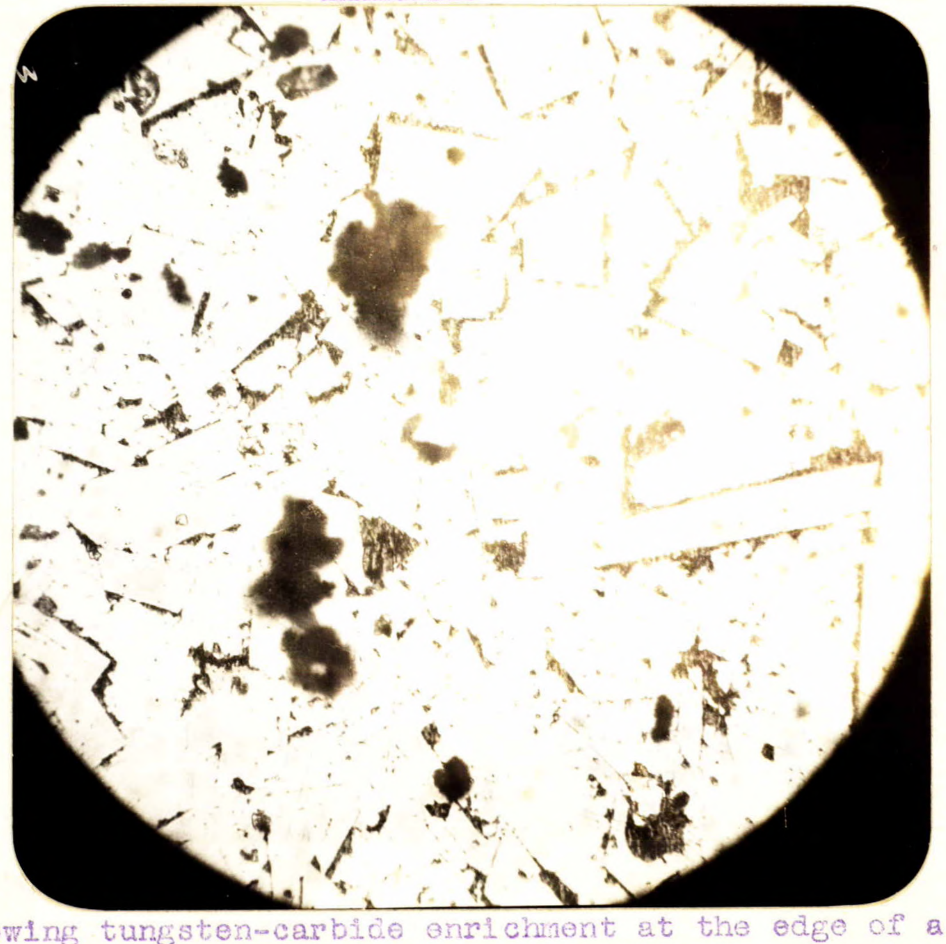
Showing nose of cast tungsten-carbide core.
(Approximately X4 magnification).

Figure 3.



Showing large irregular cavities (dark areas) in the centre of the core of cast tungsten carbide. Magnification, X40, unetched.

Figure 4.



Showing tungsten-carbide enrichment at the edge of a cast tungsten-carbide bullet core. The crystals are distinctly smaller and the amount of matrix scarcer than in Figure 5. Magnification, X500, unetched. Hardness: 1100 Vickers (50-kilogram load).
(N.B.: The polishing is sufficient to place in relief the hard tungsten carbide.)

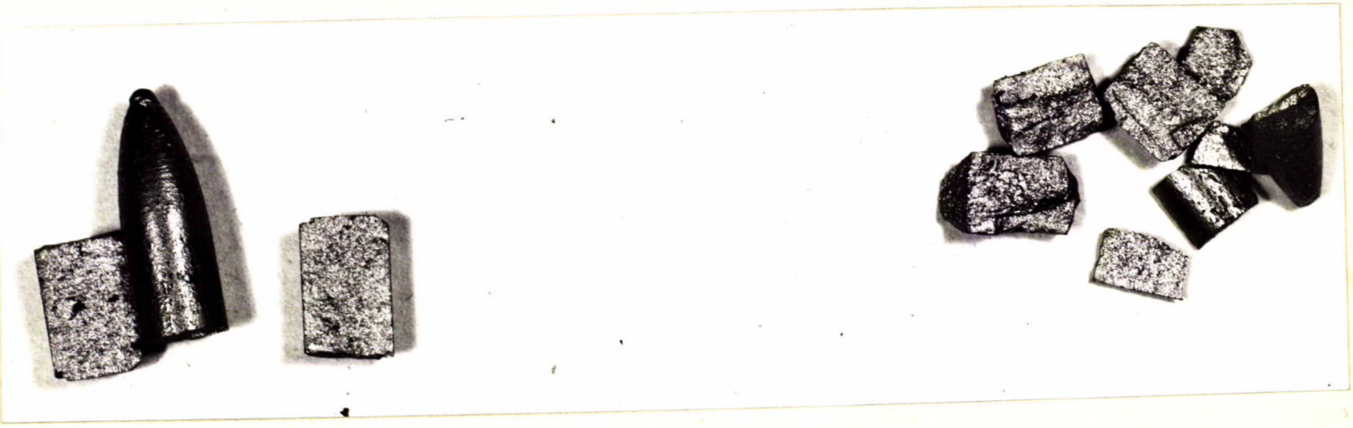
Figure 5.

Showing large tungsten-carbide crystals "floating" in the tungsten carbide - cobalt matrix (darker areas). Section taken on centre of cast tungsten-carbide bullet core. Magnification, X500, alkaline ferricyanide etch. Hardness, 800 Vickers (50-kilogram load).

Figure 6.

Showing excessively large tungsten-carbide crystals "isolated" in the dark tungsten carbide - cobalt matrix at centre of cast bullet core; also twinning of tungsten-carbide crystals, a rare occurrence. Magnification, X250, alkaline ferricyanide etch.

Figure 7.



a b

PIECES BROKEN BY A FALLING WEIGHT.

a : 2.89 foot-pounds
b : 3.86 "

APPENDIX B.

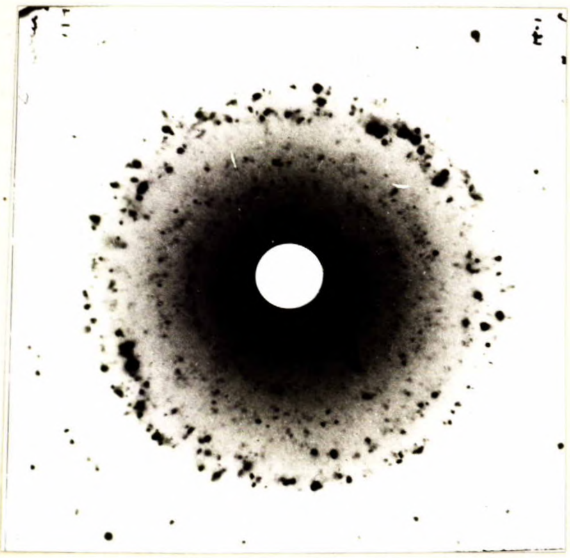
X-RAY ANALYSIS

	System, structure type	Parameters	
Mono-tungsten carbide (WC)	Hexagonal	a: 2.901	c: 2.830
Di-tungsten carbide (W_2C)⊕	Hexagonal	a: 2.99	c: 4.72
Tungsten (α)	Body-centred cubic	3.1583	
Cobalt (β)⊕⊕	Face-centred cubic	3.554	

⊕ Above 2400° C. shows an allotropic form, β W_2C.

⊕⊕ α-cobalt (hexagonal, close-packed) is stable up to 400° C. During reduction of the oxide by hydrogen at 600° C., only traces of the α-cobalt form are produced, the metal having a face-centred cubic lattice of the β-cobalt. This latter form (β-cobalt) is therefore the only one of interest in the present report.

Figure 8.



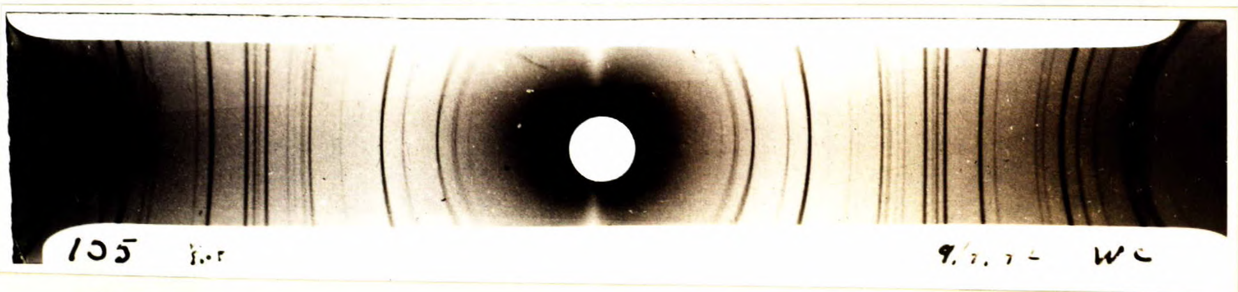
Back radiation radiograph (high order) taken at the centre of a cross-section of a cast tungsten-carbide bullet core, using an unfiltered cobalt target and a 1-mm. pinhole diaphragm. Distance from specimen to film: 30 mm. Time of exposure: 50 minutes.

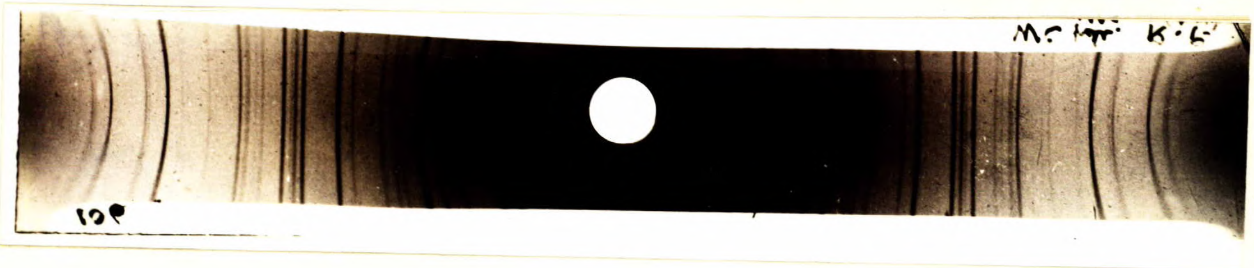
The coarse crystal structure and random orientation of these same crystals can be best seen in the 202 and 120 planes (46 mm. and 54 mm. diameters respectively) given by the CoK_{α_1} radiation on the mono-tungsten carbide constituent.

Reference Patterns -

In order to have a clear picture of the X-ray crystallographic analysis, a series of reference patterns is given and interpreted. These patterns include mono-tungsten carbide (WC) and tungsten metal.

Figures 9, 10, and 11.





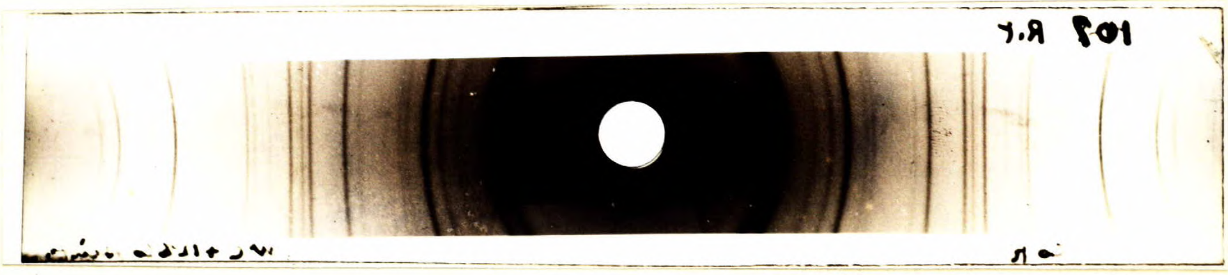


Figure 9: Debye-Scherrer radiograph taken on mono-tungsten carbide powder (6.12 per cent carbon); cobalt unfiltered radiation, outcoming ray through film. (Average particle size: 2μ).

Figure 10: Same as Figure 9 but incoming ray through film.

Figure 11: A 12 per cent cobalt sintered tungsten-carbide. Debye-Scherrer, cobalt radiation, incoming ray through film. It is noticeable that only the tungsten-carbide pattern appears in this radiograph. The β -cobalt lines are not present (see Figure 16). The CoK_{α_1} and CoK_{α_2} of the 121 plane are not resolved as in Figure 10.

(Continued on next page)

(Reference Patterns, cont'd) -

Interpretation of Patterns, Figures 9, 10, and 11.

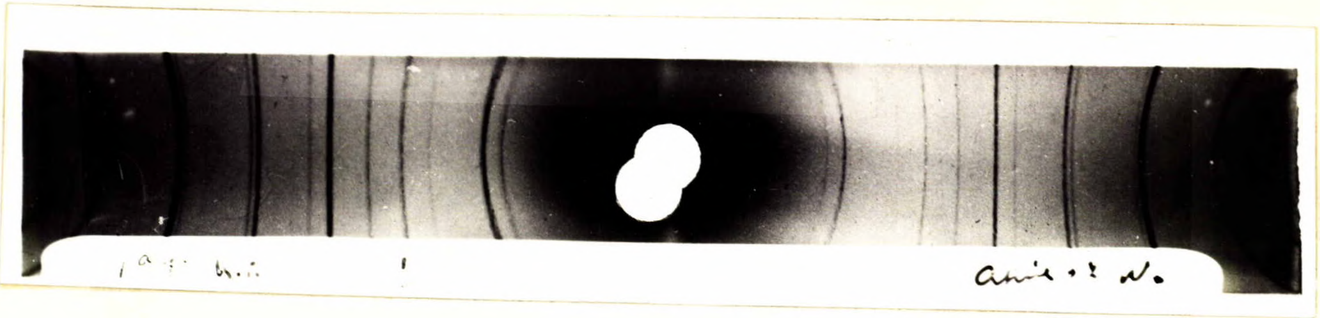
Ring No.	Intensity⊛	θ-angle, degrees	Radiation, CoK	Plane	Diameter, mm. Figure 9	Diameter, mm. Figures 10 and 11	Remarks
1	VW	16.7	β_1	001	33.4	146.6	
2	M	18.5	α_1	001	37.0	143.0	
3	W	18.8	β_1	100	37.6	142.4	
4	VS	20.8	α_1	100	41.6	138.4	
5	M	25.6	β_1	101	51.2	128.8	
6	VS	28.5	α_1	101	57.0	123.0	
7	W	33.9	β_1	110	67.8	112.2	
8	VW	35.1	β_1	002	70.2	109.8	
9	S	38.0	α_1	110	76.0	104.0	
10	W	38.8	β_1	111	77.6	102.4	
11	W	39.3	α_1	002	78.6	101.4	
12	W	40.1	β_1	020	80.2	99.8	
13	W	41.2	β_1	102	82.4	97.6	
14	S	43.8	α_1	111	87.6	92.4	
15	W	44.8	β_1	021	89.6	90.4	
16	M	45.3	α_1	020	90.6	89.4	
17	VS	46.6	α_1	102	93.2	86.8	
18	VS	51.2	α_1	021	102.4	77.6	
19	W	53.1	β_1	112	106.2	73.8	
20	W	58.4	β_1	120	116.8	63.2	
21	W	58.5	β_1	003	117.0	63.0	
22	W	59.6	β_1	202	119.2	60.8	
23	VS	62.1	α_1	112	124.2	55.8	
24	S	64.0	β_1	121	128.0	52.0	
25	S	66.9	β_1	103	133.8	46.2	
26	VS	70.1	α_1	120	140.2	39.8	
27	W	72.0	α_1	003	144.0	36.0	
28	VS	72.2	α_1	202	144.4	35.6	
29	S	72.3	α_2	202	144.6	35.4	
30	W	74.9	β_1	300	149.8	30.2	
31	VS	82.8	α_1	121	165.6	14.4	)Not resol-)ved in)Figure 11
32	S	83.8	α_2	121	167.6	12.4	)(sintered).

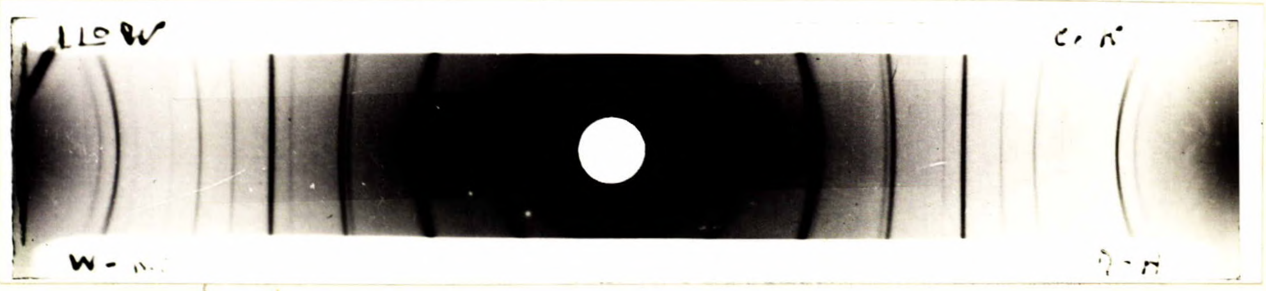
⊛ Intensity:

VS = Very strong
S = Strong
M = Medium
W = Weak
VW = Very weak.

(Reference Patterns, cont'd) -

Figures 12 and 13.





Debye-Scherrer radiographs taken on pure tungsten powder with cobalt radiation; Figure 12, outcoming ray through film; Figure 13, incoming ray through film.

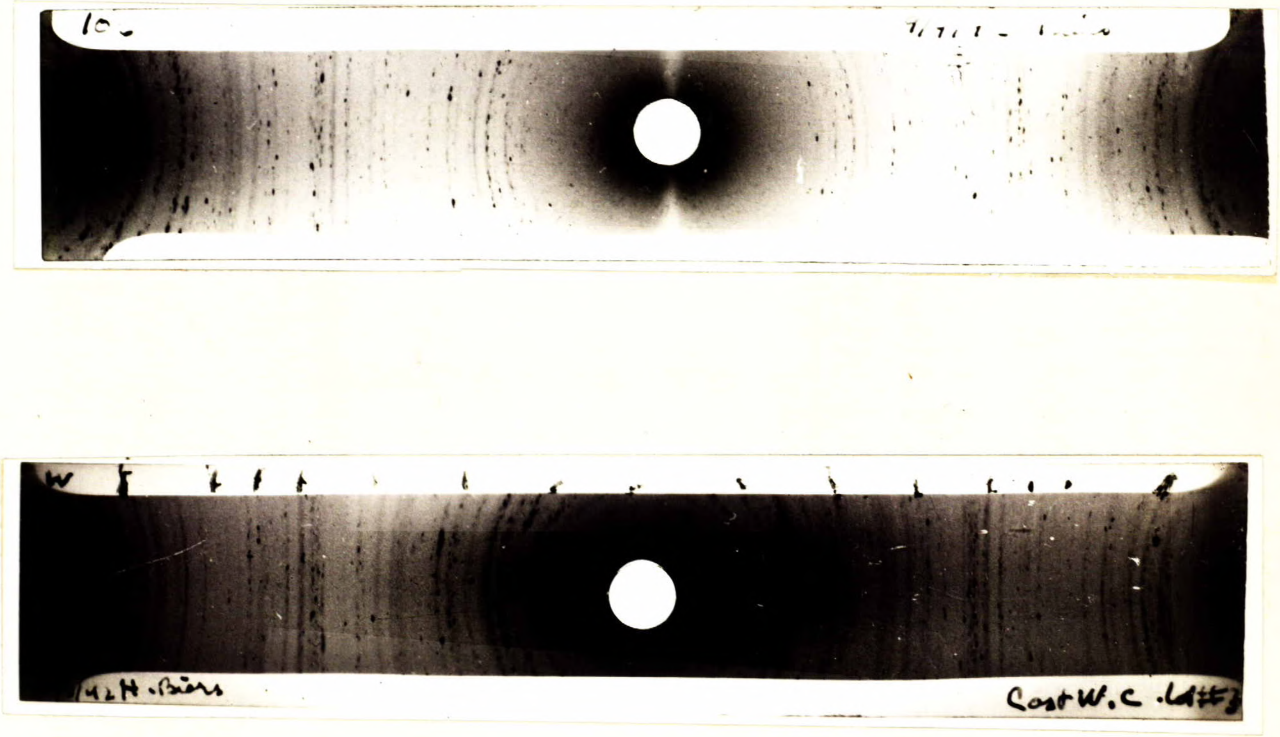
Ring No.	Intensity⊕	θ-angle, degrees	Radiation, CoK	Plane	Diameter, mm. Figure 12	Diameter, mm. Figure 13
1	M	21.2	β_1	110	42.4	137.6
2	VS	23.6	α_1	110	47.2	132.8
3	W	30.8	β_1	200	61.6	118.4
4	S	34.4	α_1	200	68.8	111.2
5	M	38.8	β_1	211	77.6	102.4
6	VS	43.8	α_1	211	87.6	92.4
7	W	46.4	β_1	220	92.8	87.2
8	S	53.0	α_1	220	106.0	74.0
9	M	54.1	β_1	310	108.2	71.8
10	W	62.5	β_1	222	125.0	55.0
11	VS	63.4	α_1	310	126.8	53.2
12	S	73.4	β_1	321	146.8	33.2
13	VS	78.3	α_1	222	156.6	23.4
14	S	78.9	α_2	222	157.8	22.2

⊕ Intensity:

VS - Very strong
S - Strong
M - Medium
W - Weak
VW - Very weak.

(Reference Patterns, cont'd) -

Figures 14 and 15.



Debye-Scherrer radiographs taken on
cast tungsten carbide.
Radiation: cobalt, unfiltered.
Figure 14: outcoming ray through hole;
Figure 15: incoming ray through hole.

Three constituents were identified in these patterns: tungsten metal (W), di-tungsten carbide (W_2C), and mono-tungsten carbide (WC). In the preparation of the sample, care was taken not to include any of the nickel deposit at the surface of the bullet core.

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(Continued on next page)

(Reference Patterns, cont'd) -

Interpretation of Patterns, Figures 14 and 15.

Ring No.	Diameter, mm. Figure 14	Diameter, mm. Figure 15	θ-angle, degrees	Constituent	Radiation, CoK	Plane	Remarks
1	21.8	158.2	10.9	W_2C	α_1	001	C.
2	33.4	146.6	16.7	WC	β_1	001	
3	37.0	143.0	18.5	WC	α_1	001	
4	37.6	142.4	18.8	WC	β_1	100	
5	40.4	139.6	20.2	W_2C	α_1	100	C.
6	41.6	138.4	20.8	WC	α_1	100	C.
7	41.8	138.2	20.9	W_2C	β_1	101	
8	44.6	135.4	22.3	W_2C	α_1	002	S.C.
9	46.4	133.6	23.2	W_2C	α_1	101	
10	47.2	132.8	23.6	W	α_1	110	
11	51.2	128.8	25.6	WC	β_1	101	
12	56.8	123.2	28.4	WC	α_1	101	
13	61.6	118.4	30.8	W_2C	α_1	102	C.
14	67.8	112.2	33.9	WC	β_1	110	
15	68.8	111.2	34.4	W	α_1	200	
16	69.2	110.8	34.6	W_2C	α_1	003	
17	70.2	109.8	35.1	WC	β_1	002	
18	73.4	106.6	36.7	W_2C	α_1	110	
19	76.0	104.0	38.0	WC	α_1	110	
20	77.6	102.4	38.8	WC	β_1	111	
21	77.8	102.2	38.9	W_2C	α_1	111	
22	78.6	101.4	39.3	WC	α_1	002	
23	80.2	99.8	40.1	WC	β_1	020	
24	82.4	97.6	41.2	WC	β_1	102	
25	83.4	96.6	41.7	W_2C	α_1	103	
26	87.4	92.6	43.7	W_2C	α_1	020	
27	87.6	92.4	43.8	WC	α_1	111	Not resolved.
28	87.8	92.2	43.9	W	α_1	211	
29	89.6	90.4	44.8	WC	β_1	021	
30	90.2	89.8	45.1	W_2C	α_1	112	
31	90.6	89.4	45.3	WC	α_1	020	
32	91.4	88.6	45.7	W_2C	α_1	021	
33	93.2	86.8	46.6	WC	α_1	102	
34	98.6	81.4	49.3	W_2C	α_1	004	
35	102.2	77.8	51.1	WC	α_1	021	
36	104.0	76.0	52.0	W_2C	α_1	202	
37	106.0	74.0	53.0	W	α_1	220	
38	106.4	73.6	53.2	WC	β_1	112	
39	111.2	68.8	55.6	W_2C	α_1	113	C.
40	112.8	67.2	56.4	W_2C	α_1	104	C.

(This table is)
(continued on next page)

(Reference Patterns, cont'd) -

Interpretation of Patterns, Figures 14 and 15, (cont'd)

Ring No.	Diameter, mm. Figure 14	Diameter, mm. Figure 15	θ-angle, degrees	Constituent	Radiation, CoK	Plane	Remarks
41	116.8	63.2	58.4	WC	β_1	120	
42	119.0	61.0	59.5	WC	β_1	003	) Not
43	119.2	60.8	59.6	WC	β_1	202	) resolved.
44	124.2	55.8	62.1	WC	α_1	112	C.
45	126.8	53.0	63.4	W	α_1	310	) Not
46	126.8	53.2	63.4	W_2C	α_1	203	) resolved.
47	128.0	52.0	64.0	WC	β_1	121	
48	132.0	48.0	66.0	W_2C	α_1	120	
49	133.8	46.2	66.9	WC	β_1	103	
50	137.8	42.2	68.9	W_2C	α_1	121	
51	140.2	39.8	70.1	WC	α_1	120	
52	142.6	37.4	71.3	W_2C	α_1	005	
53	144.0	36.0	72.0	WC	α_1	003	) Not
58	144.4	35.6	72.2	WC	α_1	202	) resolved.
59	144.6	35.4	72.3	WC	α_2	202	
60	149.8	30.2	74.9	WC	β_1	300	
61	149.6	30.4	74.8	W_2C	α_1	114	C.
62	156.6	23.4	78.3	W	α_1	222	S.C.
63	165.6	14.4	82.8	WC	α_1	121	
64	167.6	12.4	83.8	WC	α_2	121	

C. - Characteristic. S.C. - Strongly characteristic.

(Reference Patterns, cont'd) -

Figure 16.

Debye-Scherrer radiograph taken on cobalt powder reduced in hydrogen at 600° C. (β-cobalt mainly).

Radiation - unfiltered cobalt.

Interpretation of Pattern, Figure 16.

Ring No.	Diameter, mm.	Plane	Radiation CoK	θ-angle, degrees	Intensity*
1	133.4	111	β_1	23.3	M
2	128.4	111	α_1	25.8	S
3	125.8	200	β_1	27.1	W
4	119.6	200	α_1	30.2	M
5	99.9	220	β_1	40.1	W
6	89.4	220	α_1	45.3	S
7	82.0	311	β_1	49.0	W
8	76.0	222	β_1	52.0	VW
9	67.2	311	α_1	56.4	VS
10	59.0	222	α_1	60.5	S
11	49.0	400	β_1	65.5	VW
12	14.4	331	β_1	82.8	VW

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* Intensity:

VS - Very strong
S - Strong
M - Medium
W - Weak
VW - Very weak.

APPENDIX C.

BULLETING -

Figure 17.

Showing breakage during bulleting.

(Natural size).

Ottawa, Canada.
May 12th, 1942.
RP:PES.