File

DEPARTMENT OF MINES AND RESOURCES

BUREAU OF MINES

CANADA

Ottawa, February 14, 1947.

R E P O R T

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 2177.

Metallurgical Examination and Stress Analysis of a Compressed Air Reservoir.

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(Copy No. 5.)

Bureau of Mines

Mineral Dressing and
Metallurgy Division

Physical Metallurgy
Research Laboratories

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DEPARTMENT
OF
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Mines and Geology Branch

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REPORT

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Source of Material:

On January 14, 1947, Major M. A. Dolan, for Colonel C. R. Boehm, Director of Mechanical Engineering, Department of National Defence, Army, Ottawa, Ontario, submitted for examination three steel sections cut from a 9-inch compressed air reservoir.

In a letter (File HQ 130-10-59 (DME) DME/WS. 15-1-0) accompanying the material, it was stated that the reservoir had failed on a routine examination. A drawing of the reservoir, No. D.D.(C) 875A/1868, was also submitted which specified that the steel used in these reservoirs conform to British Standard Specification V.4.AT1. It was requested that a detailed metallurgical examination be carried out on the three steel samples.

Part I contains the results of a metallurgical examination of the three samples. Part II will give a stress analysis of the steel air reservoir.

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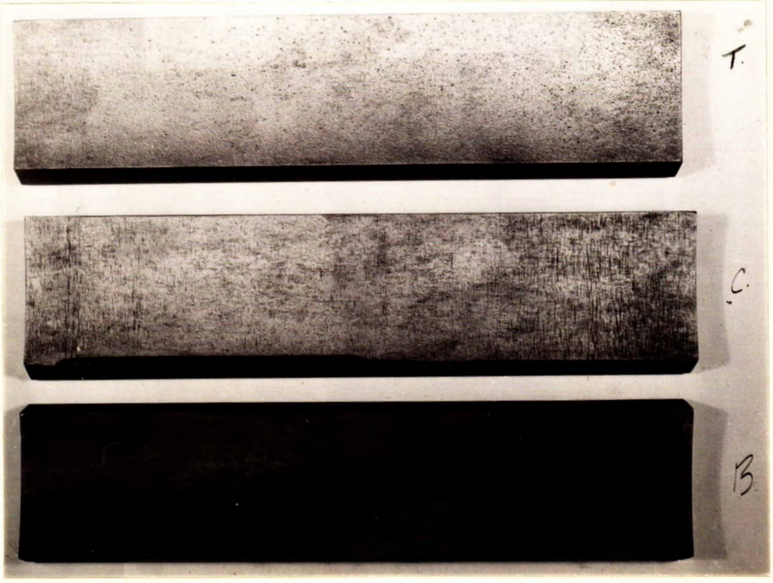
PART I - Metallurgical Examination.

Macro-Examination:

The three samples of steel plate, cut from the top (T), centre (C) and bottom (B) sections of the steel air reservoir, are shown in Figures 1 and 2 after a macro etch in 50 per cent hydrochloric acid solution. The metal was observed to be quite sound.

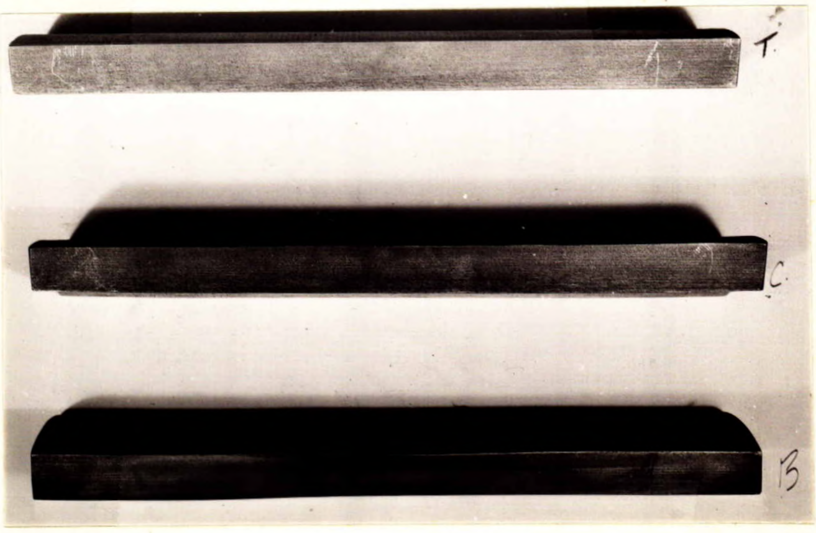
Figure 1.



MACRO-ETCHED 30 MINUTES IN
50 PER CENT HCl AT 180° F.

(Approximately 1/3 actual size.)

Figure 2.



MACRO-ETCHED 30 MINUTES IN
50 PER CENT HCl AT 180° F.

(Approximately 1/3 actual size.)

(Part I, cont'd) -

Chemical Analysis:

The results of chemical analysis of the three steel plates, and their specified chemical composition, are given in Table I.

TABLE I.

			FOUND	
	Specified, V.4.ATI	Top Section	Centre Section	Bottom Section
		-	Per Cent	-
Carbon	0.30/0.45	0.41	0.39	0.39
Manganese -	1.50 max.	0.56	0.56	0.56
Silicon -	0.10/0.35	0.21	0.21	0.21
Phosphorus -	0.06 max.	0.022	0.022	0.022
Sulphur -	0.06 max.	0.034	0.034	0.034
Nickel[⊕] -	1.00 max.	0.89	0.89	0.89
Chromium -	--	0.11	0.13	0.14
Molybdenum -	--	0.11	0.11	0.11
Vanadium -	--	Nil.	Nil.	Nil.

⊕ Optional.

Mechanical Properties:

Tensile and Izod impact tests were made on longitudinal and transverse specimens cut from each plate. Tensile tests on transverse sections were carried out on micro-specimens on the Hounsfield tensometer. The results of all mechanical tests, together with specified acceptance values for heat-treated tubes, are given in Table II.

(Table II follows,
on Page 4.)

TABLE II.

Tensile Tests	Ultimate Stress, p.s.i.	Yield Stress, p.s.i.⊕	Reduction of area, per cent	Elongation, per cent in $4\sqrt{area}$	Izod Impact Values, ⊕⊕ ft-lb.	Brinell Hardness Number
Specified H.T.	89,600 min.	56,000 min.	-	22	15	163/241
Longitudinal, Top	109,000	77,700	53.0	25	15,16½,25	197
" Centre	110,500	79,700	59.6	25	19,15,16	207
" Bottom	108,600	76,900	53.0	25	18,17,16) 23,8,15)	197
Transverse, Top	103,500	75,000	50.0	25	16	-
" Centre	112,000	87,500	54.0	23	19½	-
" Bottom	105,500	77,500	52.0	25	16	-

⊕ Yield 0.2% proof stress.

⊕⊕ Fracture of impact bars coarse-grained.

(Part I, cont'd) -

Microscopic Examination:

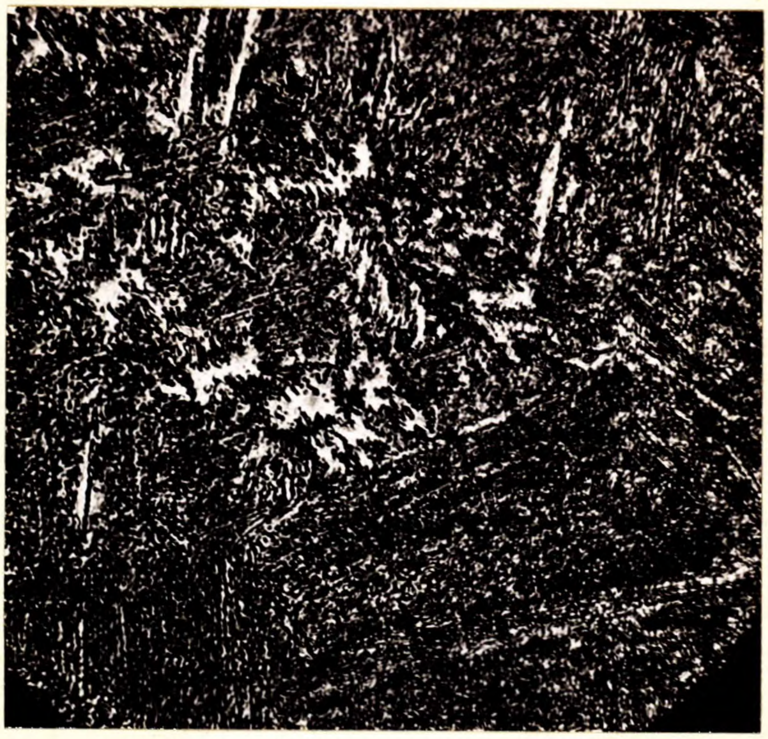
Specimens of the three steels were given a metallographic polish and examined in the unetched condition under the microscope. The steels were all fairly clean. After etching in 2 per cent nital, the steels were re-examined. The structures of the steels are shown in Figures 3 to 8 inclusive.

Figure 3.

X100, etched in
2 per cent nital.

TOP SECTION.

Figure 4.



X1000, etched in
2 per cent nital.

TOP SECTION; STRUCTURE, TEMPERED MARTENSITE.

(Part I, Microscopic Examination, cont'd) -

Figure 5.

X100, etched in 2
per cent nital.

CENTRE SECTION.

-

Figure 6.

X1000, etched in 2
per cent nital.

CENTRE SECTION; STRUCTURE, TEMPERED MARTENSITE.

-

(Part I, Microscopic Examination, cont'd) -

Figure 7.

X100, etched in 2 per cent nital.

BOTTOM SECTION, SHOWING LARGE GRAIN STRUCTURE WITH FERRITE ALONG THE GRAIN BOUNDARIES.

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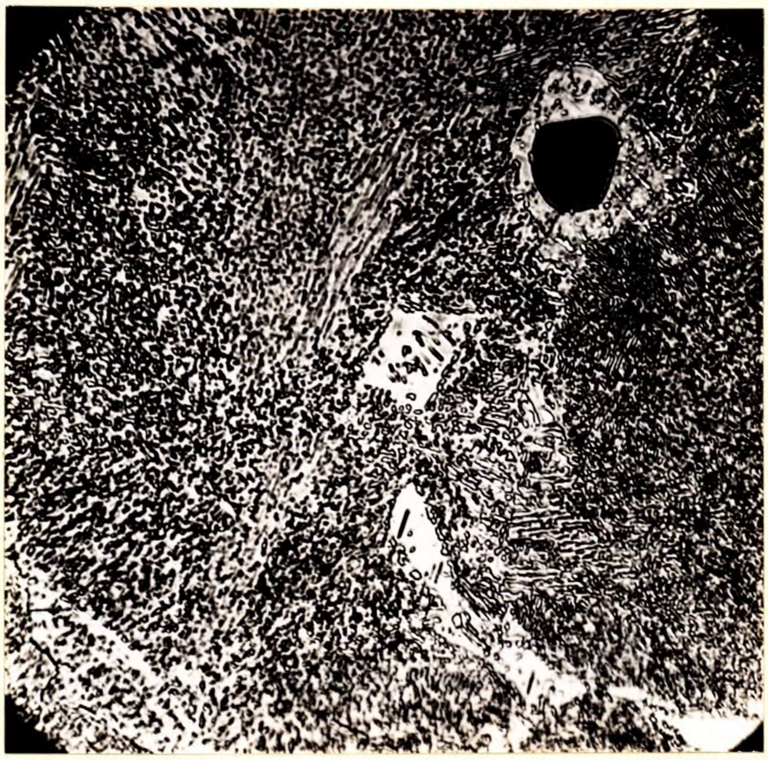
Figure 8.



-- A

X1000, etched in 2 per cent nital.

BOTTOM SECTION (Izod impact bar specimen 8 ft-lb.) SHOWING SPHEROIDIZED CARBIDES AND FERRITE, THE WHITE ETCHING MATERIAL ALONG THE GRAIN BOUNDARIES.

"A" is a non-metallic sulphide inclusion.

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(Part I, cont'd) -

Discussion of Results:

Chemical Analysis -

The chemical composition of the three plates is quite uniform and falls within the range specified for British Standard Specification V.4.AT1 steel. The amount of chromium and molybdenum found is residual and probably originated in the scrap. These elements would tend to improve the steel and are not considered harmful. The low sulphur and phosphorus contents of the metal indicate that the steel was properly made.

Macro-Examination -

The macro-examination showed that the steel reservoir had been made from sound metal.

Mechanical Properties -

The results of mechanical tests on longitudinal and transverse tensile specimens show the steel to have fairly uniform properties. The Izod impact values varied considerably. However, only one test result was less than the minimum acceptance value for tubes in the heat-treated condition.

Microstructure -

The steels were all fairly clean, an indication that the steel was properly made. The structure is typical of an oil-quenched and tempered steel. Some ferrite was observed at the grain boundaries on one section of the steel which had a low impact value. The presence of ferrite along the grain boundaries indicates that this section of the reservoir was not quenched fast enough to retain the ferrite in solution. This accounts for the low impact value obtained on this specimen.

(Part I. Metallurgical Examination, concluded) -

Conclusions from Part I:

1. The steel was properly made and had the specified chemical composition and tensile properties.

2. The impact strength of the material was found to vary considerably.

3. The irregular impact values are due to differences in structure of the steel, caused by variations in the cooling rate in the heat treatment.

4. The low impact value obtained on one section would not account for the failure encountered in the hydraulic test.

5. From the results of this metallurgical examination it is concluded that the steel meets all the specified requirements for air reservoirs.

PART II. - Stress Analysis.

Introduction:

Full particulars of the origin of this investigation are given in Part I. In brief, the compressed air reservoir concerned, a steel cylinder about 90 inches long and 10½ inches in diameter, was stated to have failed to pass the proving test. This test was carried out in accordance with Canadian Army Local Electrical and Mechanical Engineers Instruction, Armament X141 (C.A.), which specifies the gradual application of internal hydraulic pressure up to a certain value, and the measurement of the maximum and residual expansion. The residual expansion must not exceed 10 per cent of the maximum.

In the proving test on the cylinder supplied, the specified test pressure of 5,600 p.s.i. was not reached.

(Continued on next page)

(Part II, Introduction, cont'd) -

The test was discontinued at a pressure of 5,200 p.s.i. due to the excessive increase in the level of the water gauge, used to measure the volume expansion. As a result of this test the reservoir was condemned.

Samples were cut from three positions in the cylinder wall and submitted for metallurgical examination; the results of these tests are contained in Part I. This section, Part II, gives an approximate stress analysis under working conditions and under the actual test conditions.

Information Supplied:

Date of manufacture of cylinder - Jan. 8, 1940

	(2R)	External diameter -	10.5 in.
	(2r)	Internal diameter -	9.125 in.
	(t)	Wall thickness -	0.6875 in.
		Overall length -	90.0 in.
	(L)	Parallel length -	76.5 in.
(p_w)		Working pressure -	3,500 p.s.i.
(p_t)	Normal	testing pressure -	5,600 p.s.i.
(p_a)	Actual	applied pressure -	5,200 p.s.i.
(h_a)	Height of water level under pressure p_a -		38 in.
(h_o)	Height of water level after release of pressure p_a -		12.5 in.
	Internal diameter of water gauge tube -		0.797 ± 0.015 in.

Stress Analysis:

If the walls of a vessel are relatively thin (less than about one-tenth of the radius), the longitudinal and circumferential stresses are practically uniform in the parallel section throughout the thickness of the wall, and the radial stress can be ignored. If the wall thickness is more than about one-tenth of the radius, the longitudinal and circumferential stresses are not uniform throughout the wall thickness, and the radial stress cannot be

(Part II, Stress Analysis, cont'd) -

considered negligible. In the case of the cylinder submitted, the dimensions are such that it lies just over the border line between thin and thick vessels.

$$\frac{t}{R} = \frac{.6875}{5.25} = \frac{1}{7.6}$$

The formulae established for the maximum longitudinal, circumferential and radial stresses in a thick vessel under uniform internal pressure are given below:

Longitudinal stress, $S_2 = p \cdot \frac{r^2}{R^2 - r^2}$ . . . (1)
(uniform)

Circumferential stress, $S_1 = p \cdot \frac{R^2 + r^2}{R^2 - r^2}$ . . . (2)
(maximum at inner surface)

Radial stress, $S_3 = -p$ . . . (3)
(maximum at inner surface)

where p = internal pressure.

Substituting the actual values of r and R in the above equations, we obtain

$$S_1 = 7.17\ p \quad . . . (4)$$

$$S_2 = 3.09\ p \quad . . . (5)$$

$$S_3 = -p \quad . . . (6)$$

The conditions of yielding for ductile metals can, within errors of about 3 per cent, be expressed by the equation

$$(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2 = 2S_o^2 \quad . . . (7)$$

suggested by R. von Mises and H. Hencky. In equation (7), S_o is the yield stress of the material in pure tension.

This equation may be applied to the stresses developed at the inner surface; substituting the values obtained in (4), (5) and (6) gives

$$S_o = 7.07\ p \quad . . . (8)$$

Therefore, under the various pressure conditions, the

(Part II, Stress Analysis, cont'd) -

equivalent yield stresses are as follows:

Working pressure, p_w = 3,500 p.s.i.; S_o = 24,800 p.s.i.

Normal test pressure, p_t = 5,600 p.s.i.; S_o = 39,600 p.s.i.

Actual applied pressure, p_a = 5,200 p.s.i.; S_o = 36,800 p.s.i.

Strain Analysis:

An approximate analysis was also carried out to check the elastic deformation of the cylinder reported in the proving test. The change in outer radius (R) due to a pressure (p)

$$= \Delta R$$

$$= p \cdot \frac{R}{E} \left\{ \frac{r^2}{R^2 - r^2} (2 - \mu) \right\} \qquad \ldots (9)$$

where E = modulus of elasticity, p.s.i.
μ = Poisson's ratio.

Assuming a value of 30×10^6 for E, and 0.3 for μ, we obtain

$$\Delta R = 0.92\, p \times 10^{-6} \qquad \ldots (10)$$

In the actual test the applied pressure was 5,200 p.s.i., giving

$$\Delta R = 0.0048 \text{ in.} \qquad \ldots (11)$$

Neglecting the ends of the cylinder, the calculated increase in volume is given approximately by

$$L \times 2\pi R \times 0.0048 = 12.1 \text{ in.}^3 \qquad \ldots (12)$$

Since the internal diameter of the glass tube of the water gauge was 0.797 in., corresponding to an area of 0.5 in.^{2}, the equivalent height of the water column should be 24½ in. The recorded change in height was 38 - 12.5 = 25½ in., which agrees reasonably well with the calculated value.

(Part II, Stress Analysis, concluded) -

Conclusions from Part II:

1. The observed yield stress values, obtained in tensile tests on samples submitted from the faulty cylinder, were considerably greater than the calculated equivalent yield stress at the inner surface. This indicates that the strength properties of the steel were satisfactory.

2. The recorded elastic deformation of the cylinder agreed well with the approximate value calculated from theoretical considerations.

General Discussion on Cause of Failure.

The results of the metallurgical examination carried out in accordance with the request of the Director of Mechanical Engineering, Department of National Defence, Army, have not shown any obvious cause for the failure of this particular steel cylinder. A brief analysis of the stress, on the basis of the nominal dimensions, indicates that the steel used could be considered satisfactory for the purpose. There would appear to be two possible explanations:

(1) A localized reduction in wall thickness in the forming operation; measurements on the samples submitted varied from 0.675 inch to 0.705 inch, the nominal value being 0.6875 inch.

(2) An undetected fault in the cylinder testing apparatus, such as, say, a leakage of oil into the water.

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