Handbook of Reference Data for NONDESTRUCTIVE TESTING

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ASTM INTERNATIONAL

Handbook of Reference Data for Nondestructive Testing

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ASTM Data Series: DS68
ASTM Stock Number: DS68

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100 Barr Harbor Drive
PO Box C700
West Conshohocken, PA 19428-2959

Printed in the U.S.A.

Library of Congress Cataloging-in-Publication Data

Handbook of reference data for nondestructive testing / Leonard Mordfin, editor.
p. cm. — (ASTM data series ; DS 68)
"ASTM Stock Number: DS68."
Includes bibliographical references and index.
ISBN 0-8031-2092-3
1. Non-destructive testing—Handbooks, manuals, etc. I. Mordfin, Leonard. II. ASTM data series publication ; DS 68.

TA417.2.H37 2001
620.1′127—dc21
2001043939

Printed in Baltimore, MD
February 2002

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Foreword

QUALIFIED NONDESTRUCTIVE TESTING (NDT) personnel regularly demonstrate their abilities to carry out their responsibilities with accuracy and efficiency. They understand the capabilities of their equipment and the approaches that will yield the most accurate and reliable results.

Much nondestructive testing is repetitive although never routine because the needs for careful attention to detail and for alertness to tiny discrepancies are always present. On the other hand, it is not at all uncommon for the NDT professional to be faced with a new challenge—a test object that involves different materials, shapes, or dimensions, and a requirement for an immediate test. This handbook is intended to serve as a useful tool in such situations. In the absence of his or her library or computer, this little book is intended to furnish all or most of the reference data needed to proceed.

The reference data are provided here in tables, charts, graphs, and equations that will help the NDT professional to develop a promising approach and to carry out a test that is likely to produce reliable results. However, several words of caution are in order.

A considerable portion of the data documented herein are material property data: densities, acoustic velocities, X-ray absorption coefficients, magnetic permeabilities, and so on. These data have been gleaned from the literature and are believed to be reliable, but they have not been independently verified in most cases. (Note, however, that a blank page (or two) has been provided at the end of each chapter for the user to record data particular to his or her needs, which could include instrument serial numbers, characteristics, and calibrations, as well as relevant material properties.)

Testing conditions and parameters are presented here, having been compiled from recognized standards, but their appearance here is intended only to serve as reminders. They do not replace the standards that may apply. Clearly, the excerpts from standards that are given here may not comprise all of the relevant requirements, and, certainly, testing parameters outside of those cited may be authorized by the contracting organization.

Finally, it is acknowledged that, with a few exceptions, this book does not address the interpretation and evaluation of NDT indications, these activities most commonly being carried out in places where more thorough sources of reference data are easily accessible.

In closing, I wish to express my sincere appreciation to David Mackintosh, Sam Robinson, John Slotwinski, Patrick Abbott, and Charles Ehrlich, who compiled and organized entire chapters for this book. I am also indebted to many other experts who contributed to this volume, providing data, sources, and valuable reviews and comments. Two of these merit particular mention, namely, Connie Presley and, most especially, Dennis Poffenroth.

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General Data

TABLE 1.1 Fundamental physical constants.[A,B]

Avogadro constant	6.0221×10^{23} mol^{-1}
Faraday constant	96485 C mol^{-1}
Molar gas constant	8.3145 J mol^{-1} K^{-1}
Planck constant	6.6261×10^{-34} J s
Speed of light in vacuum	2.9979×10^{8} m s^{-1}
Stefan-Boltzmann constant	5.6704×10^{-8} W m^{-2} K^{-4}
Wien displacement law constant	2.8978×10^{-3} m K

[A] Source: National Institute of Standards & Technology, Physics Laboratory.
[B] SI units: J = joules, K = degrees Kelvin, W = watts.

TABLE 1.2 Characteristics of energy spectrum used in nondestructive testing ©.

Type of Energy	Frequency Range, Hz	Wavelength, cm
1. Subsonic	Under 20	Over 1.5×10^9
2. Audio	20 to 20 000	1.5×10^9 to 1.5×10^6
3. Ultrasonic	20 000 and up	Less than 1.5×10^6
4. Radio frequency	10^4 to 54×10^6	3×10^6 to 550
5. Ultra-high frequency	54×10^6 to 4.7×10^8	550 to 64
6. Very high frequency	4.7×10^8 to 1.3×10^{10}	64 to 3
7. Microwaves	10^{10} to 10^{12}	3 to 3×10^{-2}
8. Infrared	10^{12} to 4×10^{14}	3×10^{-2} to 7.5×10^{-5}
9. Visible light	4×10^{14} to 8×10^{14}	7.5×10^{-5} to 3.75×10^{-5}
10. Ultraviolet light	8×10^{14} to 5×10^{16}	3.75×10^{-5} to 6×10^{-7}
11. Soft X-rays	5×10^{16} to 3×10^{18}	6×10^{-7} to 10^{-8}
12. Industrial X-rays and gamma rays	3×10^{18} to 3×10^{21}	10^{-8} to 10^{-11}

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TABLE 1.3 Atomic number, atomic mass, and density of selected elements at normal temperatures.

Element	Atomic Number	Atomic Mass	Density, g/cm^3	Ref.	Element	Atomic Number	Atomic Mass	Density, g/cm^3	Ref.
Aluminum	13	27.0	2.70	[1][A]	Iron	26	55.8	7.87	[1]
Antimony	51	121.8	6.68	[1]	Lead	82	207.2	11.68	[1]
Arsenic	33	74.9	5.73	[1]	Lithium	3	6.9	0.53	[1]
Barium	56	137.3	3.59	[2]	Magnesium	12	24.3	1.74	[1]
Beryllium	4	9.0	1.85	[1]	Manganese	25	54.9	7.47	[1]
Bismuth	83	209.0	9.80	[1]	Molybdenum	42	95.9	10.22	[2]
Boron	5	10.8	2.47	[2]	Neodymium	60	144.2	7.00	[1]
Cadmium	48	112.4	8.64	[1]	Nickel	28	58.7	8.91	[2]
Calcium	20	40.1	1.54	[1]	Niobium	41	92.9	8.58	[2]
Carbon	6	12.0	2.27	[2]	Osmium	76	190.2	22.58	[2]
Cerium	58	140.1	6.75	[1]	Palladium	46	106.4	12.00	[2]
Chromium	24	52.0	7.19	[2]	Platinum	78	195.1	21.45	[1]
Cobalt	27	58.9	8.9	[1]	Potassium	19	39.1	0.86	[1]
Copper	29	63.6	8.96	[1]	Rhenium	75	186.2	21.02	[2]
Dysprosium	66	162.5	8.54	[1]	Rhodium	45	102.9	12.42	[2]
Erbium	68	167.3	9.05	[1]	Rubidium	37	85.5	1.53	[1]
Europium	63	152	5.25	[2]	Ruthenium	44	101.1	12.36	[2]
Gadolinium	64	157.2	7.89	[1]	Scandium	21	45.0	2.99	[1]
Gallium	31	69.7	5.91	[1]	Selenium	34	79.0	4.79	[1]
Germanium	32	72.6	5.32	[1]	Silicon	14	28.1	2.34	[1]
Gold	79	197	19.28	[2]	Silver	47	107.9	10.50	[2]
Hafnium	72	178.5	13.28	[2]	Sodium	11	23.0	0.97	[1]
Holmium	67	164.9	8.80	[1]	Strontium	38	87.6	2.58	[2]
Indium	49	114.8	7.29	[2]	Tantalum	73	181.0	16.67	[2]
Iridium	77	192.2	22.55	[1]	Terbium	65	158.9	8.27	[1]

Continues on next page

TABLE 1.3 *continued.*

Element	Atomic Number	Atomic Mass	Density, g/cm^3	Ref.
Tellurium	52	127.6	6.24	[1]
Thallium	81	204.4	11.87	[2]
Thorium	90	232.0	11.72	[2]
Tin	50	118.7	7.29	[2]
Titanium	22	47.9	4.51	[2]
Tungsten	74	183.8	19.25	[2]
Uranium	92	238.0	19.05	[1]
Vanadium	23	50.9	6.09	[2]
Ytterbium	70	173.0	6.98	[1]
Yttrium	39	88.9	4.48	[1]
Zinc	30	65.4	7.14	[1]
Zirconium	40	91.2	6.49	[1]

[A] Numbers in brackets designate references listed at the end of the chapter.

TABLE 1.4A Density of cast aluminum alloys at normal temperatures.

Alloy				Alloy			
ANSI No.	UNS[A] No.	Density, g/cm^3	Ref.	ANSI No.	UNS No.	Density, g/cm^3	Ref.
201	A02010	2.80	[3]	A384	A13840	2.77	[4]
206	A02060	2.80	[4]	390	A03900	2.73	[4]
A206	A12060	2.80	[4]	A390	A13900	2.73	[4]
208	A02080	2.79	[5]	392	A03920	2.64	[3]
222	A02220	2.94	[6]	413	A04130	2.65	[6]
224	A02240	2.81	[3]	A413	A14130	2.65	[6]
238	A02380	2.95	[5]	443	A04430	2.69	[4]
240	A02400	2.78	[3]	A443	A14430	2.69	[4]
242	A02420	2.82	[4]	B443	A24430	2.69	[6]
295	A02950	2.81	[5]	C443	A34430	2.69	[4]
B295	A22950	2.80	[4]	A444	A14440	2.68	[3]
296	A02960	2.80	[5]	511	A05110	2.68	[3]
308	A03080	2.79	[5]	512	A05120	2.65	[6]
319	A03190	2.79	[7]	513	A05130	2.68	[3]
324	A03240	2.67	[3]	514	A05140	2.65	[5]
332	A03320	2.76	[3]	B514	A25140	2.65	[6]
A332	A13320	2.71	[4]	518	A05180	2.57	[4]
333	A03330	2.77	[8]	520	A05200	2.57	[6]
336	A03360	2.72	[3]	535	A05350	2.62	[4]
354	A03540	2.71	[3]	A535	A15350	2.62	[4]
355	A03550	2.71	[7]	B535	A25350	2.62	[4]
C355	A33550	2.71	[8]	705	A07050	2.76	[3]
356	A03560	2.68	[6]	707	A07070	2.77	[3]
A356	A13560	2.67	[8]	710	A07100	2.81	[3]
357	A03570	2.68	[4]	711	A07110	2.84	[3]
A357	A13570	2.68	[4]	712	A07120	2.82	[3]
358	A03580	2.68	[3]	D712	A47120	2.81	[4]
359	A03590	2.68	[4]	713	A07130	2.81	[4]
360	A03600	2.64	[8]	771	A07710	2.82	[5]
A360	A13600	2.63	[8]	850	A08500	2.88	[4]
364	A03640	2.63	[8]	851	A08510	2.83	[3]
380	A03800	2.72	[8]	852	A08520	2.88	[3]
A380	A13800	2.71	[8]				
383	A03830	2.74	[4]				
384	A03840	2.70	[8]				

[A] UNS = Unified Numbering System.

TABLE 1.4B Density of wrought aluminum alloys at normal temperatures.

Alloy				Alloy			
AA[X] No.	UNS No.	Density, g/cm^3	Ref.	AA No.	UNS No.	Density, g/cm^3	Ref.
2011	A92011	2.83	[8]	5556	A95556	2.66	[8]
2014	A92014	2.80	[8]	5652	A95652	2.68	[8]
2017	A92017	2.79	[8]	5654	A95654	2.66	[8]
2018	A92018	2.81	[8]	5657	A95657	2.69	[8]
2024	A92024	2.77	[6]	6003	A96003	2.69	[8]
2025	A92025	2.81	[8]	6005	A96005	2.70	[8]
2031	A92031	2.75	[6]	6009	A96009	2.71	[8]
2036	A92036	2.75	[8]	6010	A96010	2.70	[8]
2117	A92117	2.75	[8]	6053	A96053	2.69	[8]
2124	A92124	2.77	[8]	6061	A96061	2.70	[8]
2218	A92218	2.80	[8]	6063	A96063	2.70	[6]
2219	A92219	2.84	[8]	6066	A96066	2.72	[8]
2618	A92618	2.75	[6]	6070	A96070	2.71	[8]
3003	A93003	2.73	[8]	6082	A96082	2.70	[6]
3004	A93004	2.72	[8]	6101	A96101	2.70	[6]
3005	A93005	2.73	[8]	6105	A96105	2.69	[8]
3103	A93103	2.73	[6]	6151	A96151	2.70	[8]
3105	A93105	2.72	[8]	6162	A96162	2.70	[8]
4032	A94032	2.68	[8]	6201	A96201	2.69	[8]
4043	A94043	2.68	[8]	6262	A96262	2.72	[8]
4045	A94045	2.67	[8]	6351	A96351	2.71	[8]
4047	A94047	2.66	[8]	6463	A96463	2.69	[8]
4145	A94145	2.74	[8]	6951	A96951	2.70	[8]
4343	A94343	2.67	[8]	7005	A97005	2.78	[8]
4643	A94643	2.69	[8]	7008	A97008	2.78	[8]
5005	A95005	2.70	[8]	7011	A97011	2.77	[8]
5050	A95050	2.69	[8]	7016	A97016	2.81	[8]
5052	A95052	2.68	[8]	7020	A97020	2.78	[6]
5056	A95056	2.64	[8]	7049	A97049	2.84	[4]
5083	A95083	2.66	[8]	7050	A97050	2.83	[4]
5086	A95086	2.66	[8]	7072	A97072	2.72	[8]
5154	A95154	2.66	[8]	7075	A97075	2.80	[6]
5183	A95183	2.66	[8]	7178	A97178	2.83	[8]
5252	A95252	2.67	[8]	8000	A98000	2.71	[10]
5254	A95254	2.66	[8]	8017	A98017	2.71	[4]
5356	A95356	2.64	[8]	8030	A98030	2.71	[4]
5357	A95357	2.70	[9]	8079	A98079	2.72	[10]
5454	A95454	2.69	[8]	8111	A98111	2.71	[10]
5456	A95456	2.66	[8]	8176	A98176	2.71	[4]
5457	A95457	2.69	[8]	8177	A98177	2.70	[4]
5554	A95554	2.69	[8]				

[X] AA = Aluminum Association.

TABLE 1.4C Density of cast copper and copper alloys at normal temperatures.

UNS No.	Common Name	Density, g/cm^3	Ref.	UNS No.	Common Name	Density, g/cm^3	Ref.
C80100	**Coppers**	8.94	[11]		**Bronzes**		
C80410		8.94	[11]	C90200	tin bronze	8.80	[11]
C80500		8.94	[5]	C90300		8.80	[11]
C81100		8.94	[11]	C90500		8.72	[11]
C81300		8.81	[5]	C90700		8.77	[11]
				C90900		8.75	[5]
C81400	**High copper alloys**	8.80	[11]	C91600		8.86	[11]
C81500		8.82	[11]	C91700		8.75	[11]
C81540		8.71	[11]				
C81800		8.62	[4]	C92200	leaded tin bronze	8.64	[11]
C82000		8.61	[11]	C92300		8.77	[11]
C82200		8.75	[11]	C92500		8.70	[11]
				C92600		8.72	[11]
C82400	beryllium copper	8.26	[11]	C92700		8.78	[11]
C82500		8.09	[11]	C92900		8.86	[11]
C82600		8.08	[11]				
C82700		8.08	[11]	C93200	hi-leaded tin bronze	8.91	[11]
C82800		8.08	[11]	C93400		8.86	[11]
				C93500		8.86	[11]
	Brasses			C93600		9.00	[11]
C83300	red brass	8.80	[11]	C93700		8.86	[11]
C83400		8.80	[11]	C93800		9.25	[11]
C83450		8.83	[11]	C93900		9.25	[11]
C83600		8.83	[11]	C94300		9.30	[11]
C83800		8.64	[11]	C94400		8.86	[11]
C84200	semi-red brass	8.61	[11]	C94500		9.41	[11]
C84400		8.69	[11]	C94700	nickel-tin bronze	8.86	[11]
C84500		8.64	[11]	C94800		8.86	[11]
C84800		8.58	[11]	C95200	aluminum bronze	7.64	[11]
C85200	yellow brass	8.50	[11]	C95300		7.53	[11]
C85400		8.44	[11]	C95400		7.52	[12]
C85500		8.41	[11]	C95410		7.45	[11]
C85700		8.41	[11]	C95500		7.53	[11]
C85800		8.44	[11]	C95600		7.70	[11]
C86100	manganese bronze	7.97	[11]	C95700		7.53	[11]
C86200		7.97	[11]	C95800		7.64	[11]
C86300		7.83	[11]				
C86400		8.33	[11]	C96200	**Copper nickels**	8.94	[11]
C86500		8.33	[11]	C96300		8.94	[11]
C86700		8.33	[11]	C96400		8.94	[11]
C86800		8.03	[11]	C96600		8.80	[11]
C87300	silicon bronze & brass	8.36	[4]				
C87400		8.30	[11]	C97300	**Nickel silvers**	8.89	[11]
C87500		8.28	[11]	C97400		8.86	[11]
C87600		8.30	[11]	C97600		8.89	[11]
C87610		8.36	[11]	C97800		8.86	[11]
C87800		8.30	[11]				
C89320	copper-bismuth alloy	8.80	[11]	C99300	Incrament 800	7.61	[11]
C89510	Cu-Bi-Se-alloy	8.66	[11]	C99400	NDZ	8.30	[11]
C89520		8.70	[11]	C99500		8.30	[11]
C89844	copper-bismuth alloy	8.58	[11]	C99700	Manganese brass	8.19	[11]
C89940		8.86	[11]	C99750		8.03	[11]

TABLE 1.4D Density of wrought copper alloys at normal temperatures.

UNS No.	Common Name	Density, g/cm^3	Ref.
	High copper alloys		
C16200	cadmium copper	8.89	[13]
C16500		8.89	[13]
C17000	beryllium copper	8.22	[14]
C17200		8.22	[14]
C17300		8.22	[14]
C17400		8.81	[13]
C17500		8.75	[14]
C18200	chromium copper	8.89	[13]
C19200	copper iron alloy	8.86	[14]
C19400		8.91	[14]
C19500		8.91	[14]
C19600		8.87	[14]
C19700		8.83	[14]
	Brasses		
C21000	gilding brass	8.86	[14]
C22000	commercial bronze	8.80	[14]
C22600	jewelry bronze	8.78	[13]
C23000	red brass	8.75	[14]
C24000	low brass	8.66	[14]
C26000	cartridge brass	8.53	[14]
C26800	yellow brass	8.47	[14]
C27000		8.47	[14]
C27200		8.44	[14]
C28000	Muntz metal	8.39	[14]
	Leaded brasses		
C31400		8.83	[14]
C31600		8.86	[14]
C32000		8.77	[14]
C33000		8.50	[14]
C33200		8.53	[14]
C33500		8.47	[14]
C34000		8.47	[14]
C34200		8.50	[14]
C34500		8.47	[14]
C35000		8.44	[14]
C35300		8.47	[14]
C35600		8.50	[14]
C36000	free-cutting brass	8.50	[14]
C36500		8.41	[13]
C37000		8.41	[14]
C37700	forging brass	8.44	[14]
C38000	architectural bronze	8.44	[14]
C38500		8.47	[14]
	Tin brasses		
C40500		8.83	[14]
C40800		8.86	[14]
C41100		8.80	[14]
C41300		8.80	[14]
C41500		8.80	[14]
C42200		8.80	[14]
C42500		8.77	[14]
C43000		8.75	[14]
C43400		8.75	[14]
C43500		8.66	[13]
C44300	admiralty brass	8.53	[14]
C44400		8.53	[14]
C44500		8.53	[14]
C46200	naval brass	8.44	[14]
C46400		8.41	[14]
C48200		8.44	[14]
C48500		8.44	[14]
	Bronzes		
C50500	phosphor bronze	8.89	[14]
C51000		8.86	[14]
C51100		8.86	[14]
C52100		8.80	[14]
C52400		8.77	[14]
C53200		8.94	[14]
C53400		8.91	[14]
C54400		8.86	[14]

Continues on next page

TABLE 1.4D *continued.*

UNS No.	Common Name	Density, g/cm^3	Ref.	UNS No.	Common Name	Density, g/cm^3	Ref.
C60600	aluminum bronze	8.17	[14]	**Copper nickels**			
C60800		8.17	[14]	C70250		8.80	[14]
C61000		7.78	[14]	C70260		8.86	[14]
C61300		7.89	[14]	C70400		8.94	[14]
C61400		7.89	[14]	C70600		8.94	[14]
C61500		7.65	[13]	C71000		8.94	[14]
C61800		7.53	[13]	C71500		8.94	[14]
C62300		7.66	[14]	C71640		8.94	[14]
C62400		7.45	[14]	C72000		8.94	[14]
C62500		7.21	[13]	C72200		8.94	[14]
C63000		7.58	[14]	C72400		8.59	[14]
C63200		7.64	[14]	C72500		8.89	[14]
C63600		8.33	[13]	C72600		8.89	[13]
C63800		8.28	[14]	C72650		8.86	[14]
C64200		7.69	[14]	C72700		8.89	[14]
C64210		7.69	[14]	C72900		8.94	[14]
C64400		8.03	[13]				
				Nickel silvers			
C64700	silicon bronze	8.91	[14]	C73500		8.83	[14]
C65100		8.75	[14]	C74000		8.69	[14]
C65400		8.55	[14]	C74500		8.66	[14]
C65500		8.53	[14]	C75200		8.75	[14]
C65800		8.53	[14]	C75400		8.70	[13]
C66100		8.53	[14]	C75700		8.69	[14]
				C76200		8.58	[14]
Miscellaneous brasses				C76400		8.72	[14]
C66700	manganese brass	8.53	[14]	C77000		8.69	[14]
C67000	manganese bronze	7.92	[14]	C77400		8.47	[14]
C67500		8.36	[14]	C78200		8.69	[13]
C68700	aluminum brass	8.33	[14]	C79200		8.72	[14]
C68800		8.19	[14]	C79400		8.77	[14]
C69000		8.20	[14]				
C69400	silicon red brass	8.19	[14]				
C69700		8.30	[14]				

TABLE 1.4E Density of magnesium alloys at normal temperatures.

UNS No.	Alloy No.	Density, g/cm^3	Ref.	UNS No.	Alloy No.	Density, g/cm^3	Ref.
M10100	AM100A	1.81	[15]	M13320	HZ32A	1.83	[15]
M10410	AS41A	1.78	[15]	M14141	LA141A	1.35	[18]
M10411	AS41B	1.78	[15]	M15100	M1A	1.75	[19]
M10600	AM60A	1.78	[15]	M16100	ZE10A	1.76	[17]
M11310	AZ31A	1.78	[1]	M16210	ZK21A	1.78	[18]
M11311	AZ31B	1.77	[15]	M16331	ZC63A	1.87	[15]
M11610	AZ61A	1.81	[15]	M16410	ZE41A	1.84	[15]
M11630	AZ63A	1.84	[15]	M16510	ZK51A	1.83	[15]
M11800	AZ80A	1.83	[15]	M16600	ZK60A	1.83	[15]
M11810	AZ81A	1.80	[15]	M16601	ZK60B	1.83	[15]
M11900	AZ90	1.81	[16]	M16610	ZK61A	1.83	[15]
M11910	AZ91A	1.81	[15]	M16620	ZH62A	1.88	[15]
M11912	AZ91B	1.81	[15]	M16630	ZE63A	1.88	[15]
M11914	AZ91C	1.81	[15]	M18210	QH21A	1.82	[15]
M11919	AZ91E	1.81	[15]	M18220	QE22A	1.82	[15]
M11920	AZ92A	1.82	[15]	M18330	EQ21A	1.81	[15]
M12330	EZ33A	1.84	[15]	M18410	WE54A	1.85	[15]
M13210	HM21A	1.77	[17]	M18430	WE43A	1.84	[15]
M13310	HK31A	1.79	[15]				
M13312	HM31A	1.80	[17]				

TABLE 1.4F Density of titanium alloys at normal temperatures.

UNS No.	Approximate Composition, % (balance Ti)	Density, g/cm^3	Ref.
R54520	5Al-2.5Sn	4.46	[19]
R54560	5Al-5Sn-2Zr-2Mo-0.2Si	4.51	[4]
R54620	6Al-2Sn-4Zr-2Mo	4.53	[20]
R54790	11Sn-2Al-5Zr-1Mo-0.2Si	4.84	[1]
R54810	8Al-1Mo-1V	4.37	[4]
R56080	8Mn	4.74	[19]
R56210	6Al-2Nb-1Ta-0.8Mo	4.48	[4]
R56260	6Al-2Sn-4Zr-6Mo	4.65	[4]
R56320	3Al-2.5V	4.48	[4]
R56400	6Al-4V	4.43	[19]
R56430	4Al-3Mo-1V	4.51	[21]
R56440	4Al-4Mn	4.51	[19]
R56620	6Al-6V-2Sn	4.54	[4]
R56740	7Al-4Mo	4.48	[21]
R58010	13V-11Cr-3Al	4.82	[4]
R58030	12Mo-6Zr-4Sn	5.06	[4]
R58640	3Al-8V-6Cr-4Mo-4Zr	4.82	[4]
	2Al-2Mn	4.51	[1]
	11Sn-4Mo-2Al-0.2Si	4.86	[1]
	6Al-5Zr-0.5Mo-0.2Si	4.45	[1]
	6Al-4Sn-3Zr-1Nb-0.3Mo-0.3Si	4.53	[1]
	6Al-4Sn-4Zr-1Nb-0.5Mo-0.4Si	4.55	[1]
	6Al-2Sn-2Zr-2Mo-2Cr-0.2Si	4.57	[4]
	4Al-4Mo-2Sn-0.5Si	4.60	[1]
	4Al-4Mo-4Sn-0.5Si	4.62	[1]
	8Mo-8V-2Fe-3Al	4.84	[4]
	10V-2Fe-3Al	4.65	[20]
	15V-3Cr-3Al-3Sn	4.76	[20]
	2.5Al-16V	4.65	[21]
	2Fe-2Cr-2Mo	4.65	[21]

TABLE 1.5A Density of irons at normal temperatures.[A,B]

Material	Density, g/cm^3	Ref.
Ingot	7.87	[21]
Gray cast iron		
High carbon ferritic	6.80	[22]
Medium carbon	7.05	[22]
Low carbon pearlitic	7.28–7.4	[22]
High aluminum	5.5–6.4	[22]
High nickel, “Ni-Resist”	7.5–7.6	[23]
High phosphorous	7.06–7.19	[23]
Medium silicon	6.9–7.2	[23]
High silicon, “Silal”	6.8–7.2	[22]
Ni-Cr-Si iron, “Nicrosilal”	7.2–7.4	[23]
Malleable cast iron		
Ferritic	7.27	[22]
Pearlitic	7.35–7.44	[5]
Ductile cast iron	7.1–7.2	[23]
Austempered	6.9	[5]
Austenitic	7.2	[5]
High carbon ferritic	7.10	[22]
High carbon pearlitic	7.15	[22]
High nickel	7.4–7.7	[24]
Medium silicon	7.1	[24]
High silicon	7.1	[22]
White cast iron	7.58–7.73	[23]
Low carbon	7.6–7.8	[24]
Ni-Cr martensitic, “Ni-hard”	7.6–7.8	[23]
High chromium ferritic	7.3–7.5	[22]
Wrought iron	7.7	[21]

[A] See Table 1.6C for iron-base superalloys.

[B] Densities of cast irons are variable due to porosity.

TABLE 1.5B Density of carbon steels at normal temperatures.

AISI/SAE No.	UNS No.	Density, g/cm^3	Ref.	AISI/SAE No.	UNS No.	Density, g/cm^3	Ref.
1005	G10050	7.87	[25]	1064	G10640	7.83	[5]
1006	G10060	7.87	[1]	1065	G10650	7.83	[5]
1008	G10080	7.86	[1]	1070	G10700	7.83	[5]
1010	G10100	7.83	[5]	1078	G10780	7.85	[1]
1015	G10150	7.82	[5]	1080	G10800	7.82	[5]
1016	G10160	7.82	[5]	1086	G10860	7.83	[5]
1017	G10170	7.83	[5]	1095	G10950	7.83	[5]
1018	G10180	7.82	[5]	1117	G11170	7.85	[5]
1020	G10200	7.82	[5]	1118	G11180	7.85	[5]
1021	G10210	7.86	[25]	1132	G11320	7.82	[5]
1022	G10220	7.86	[1]	1137	G11370	7.82	[5]
1023	G10230	7.86	[25]	1139	G11390	7.82	[5]
1025	G10250	7.86	[26]	1140	G11400	7.82	[5]
1026	G10260	7.86	[25]	1141	G11410	7.81	[5]
1029	G10290	7.82	[5]	1144	G11440	7.82	[5]
1030	G10300	7.82	[5]	1146	G11460	7.82	[5]
1035	G10350	7.83	[5]	1151	G11510	7.81	[5]
1037	G10370	7.83	[5]	1330	G13300	7.83	[5]
1038	G10380	7.84	[25]	1335	G13350	7.83	[5]
1039	G10390	7.84	[25]	1340	G13400	7.82	[5]
1040	G10400	7.84	[25]	1345	G13450	7.83	[5]
1042	G10420	7.85	[1]	1522	G15220	7.82	[5]
1043	G10430	7.83	[5]	1524	G15240	7.85	[1]
1044	G10440	7.83	[5]	1548	G15480	7.83	[5]
1045	G10450	7.83	[5]	1551	G15510	7.83	[5]
1046	G10460	7.83	[5]	1552	G15520	7.83	[5]
1050	G10500	7.84	[5]	1561	G15610	7.83	[5]
1053	G10530	7.83	[5]	1566	G15660	7.83	[5]
1055	G10550	7.83	[5]				
1060	G10600	7.82	[5]				

TABLE 1.5C Density of alloy steels at normal temperatures.

AISI/SAE No.	UNS No.	Density, g/cm^3	Ref.	AISI/SAE No.	UNS No.	Density, g/cm^3	Ref.
3140	G31400	7.82	[5]	5132	G51320	7.84	[1]
4023	G40230	7.84	[5]	5134	G51350	7.84	[5]
4027	G40270	7.84	[5]	5140	G51400	7.85	[1]
4028	G40280	7.81	[5]	5145	G51450	7.83	[5]
4032	G40320	7.81	[5]	5147	G51470	7.83	[5]
4037	G40370	7.85	[1]	5150	G51500	7.82	[5]
4042	G40420	7.81	[5]	5160	G51600	7.84	[5]
4047	G40470	7.81	[5]	6120	G61200	7.82	[5]
4130	G41300	7.83	[26]	6150	G61500	7.82	[5]
4135	G41350	7.84	[5]	8115	G81150	7.84	[5]
4137	G41420	7.83	[1]	8615	G86150	7.82	[5]
4140	G41400	7.83	[26]	8617	G86170	7.83	[5]
4142	G41420	7.84	[5]	8625	G86250	7.82	[5]
4145	G41450	7.84	[5]	8627	G86270	7.85	[5]
4147	G41470	7.84	[5]	8630	G86300	7.83	[26]
4150	G41500	7.84	[5]	8637	G86370	7.86	[1]
4161	G41610	7.84	[5]	8642	G86420	7.84	[5]
4320	G43200	7.82	[5]	8650	G86500	7.85	[5]
4337	G43370	7.84	[1]	8655	G86880	7.85	[5]
4340	G43400	7.83	[26]	8720	G87200	7.82	[5]
4422	G44220	7.84	[5]	8735	G87350	7.83	[26]
4427	G44270	7.84	[5]	8740	G87400	7.83	[26]
4617	G41670	7.83	[1]	8742	G87420	7.82	[5]
4626	G46260	7.82	[5]	8822	G88220	7.85	[5]
4718	G47180	7.84	[5]	9255	G92550	7.82	[5]
4815	G48150	7.86	[5]	9262	G92620	7.82	[5]
4820	G48200	7.86	[5]	9840	G98400	7.84	[1]
5046	G50460	7.81	[5]				
5120	G51200	7.84	[5]				
5130	G51300	7.84	[5]				

TABLE 1.5D Density of cast stainless steels at normal temperatures [5].

ACI No.	UNS No.	Density, g/cm^3
CA-15	J91150	7.60
CA-40	J91153	7.60
CB-30	J91803	7.52
CC-50	J92615	7.52
CD-4MCu	J93370	7.74
CE-30	J93423	7.66
CF-16F	J92701	7.74
CF-20	J92602	7.74
CF-3	J92500	7.74
CF-3M	J92800	7.74
CF-8	J92600	7.74
CF-8C	J92710	7.74
CF-8M	J92900	7.75
CF-10SMnN	J92972	7.62
CG-6MMN	J93790	7.89
CH-20	J93402	7.71
CK-20	J94402	7.74
HC	J92605	7.53
HD	J93005	7.58
HE	J93403	7.67
HF	J92603	7.74
HH	J93503	7.72
HI	J94003	7.71
HK	J94224	7.75
HN	J94213	7.83

TABLE 1.5E Density of wrought stainless steels at normal temperatures.

Type	UNS No.	Density, g/cm^3	Ref.	Type	UNS No.	Density, g/cm^3	Ref.
201	S20100	7.94	[5]	430F	S43020	7.7	[21]
202	S20200	7.7	[27]	431	S43100	7.80	[5]
205	S20500	7.8	[28]	434	S43400	7.7	[27]
301	S30100	7.83	[26]	436	S43600	7.7	[27]
302	S30200	7.92	[1]	439	S43035	7.8	[30]
302B	S30215	8.0	[5]	440A	S44002	7.68	[5]
303	S30300	8.0	[27]	440B	S44003	7.68	[5]
304	S30400	8.06	[29]	440C	S44004	7.68	[5]
304L	S30403	8.0	[30]	442	S44200	7.71	[5]
302Cu	S30430	8.0	[28]	444	S44400	7.8	[28]
304N	S30451	8.0	[28]	446	S44600	7.47	[5]
305	S30500	8.0	[27]	Custom 450	S45000	7.8	[30]
308	S30800	8.0	[27]	Custom 455	S45500	7.8	[30]
309	S30900	7.94	[5]	501	S50100	7.8	[5]
309S	S30908	8.0	[30]	502	S50200	7.7	[1]
310	S31000	7.98	[5]	615	S41800	7.87	[31]
310S	S31008	8.0	[30]	616	S42200	7.78	[5]
314	S31400	7.72	[21]	630	S17400	7.77	[5]
316	S31600	8.0	[27]	633	S35000	7.81	[5]
316L	S31603	8.0	[30]	634	S35500	7.79	[5]
				635	S17600	7.65	[5]
316N	S31651	8.0	[28]	PH 13-8 Mo	S13800	7.78	[29]
317	S31700	8.0	[30]	PH 15-7 Mo	S15700	7.7	[27]
317L	S31703	8.0	[30]	cond. A		7.80	[26]
321	S32100	7.92	[26]	TH 1050		7.69	[26]
329	S32900	7.8	[30]	RH 950		7.68	[26]
347	S34700	8.00	[5]	15-5 PH	S15500	7.7	[27]
AM350	S35000	7.81	[26]	17-4 PH	S17400	7.7	[27]
AM355	S35500	7.7	[27]	cond. A		7.78	[26]
384	S38400	8.0	[28]	H.900		7.80	[26]
403	S40300	7.74	[1]				
405	S40500	7.75	[5]	17-7 PH	S17700	7.81	[21]
406		7.42	[1]	cond. A		7.81	[26]
409	S40900	7.7	[27]	TH 1050		7.65	[26]
410	S41000	7.78	[29]	RH 950		7.65	[26]
414	S41400	7.7	[27]				
416	S41600	7.73	[5]	18Cr-2Mo	S18200	7.8	[30]
420	S42000	7.7	[27]	19-9 DL	S63198	7.94	[26]
422	S42200	7.78	[5]	19-9 DX	S63199	7.94	[26]
429	S42900	7.8	[28]				
430	S43000	7.78	[29]				

TABLE 1.5F Density of tool steels at normal temperatures.

AISI Type	UNS No.	Density, g/cm^3	Ref.	AISI Type	UNS No.	Density, g/cm^3	Ref.
A2	T30102	7.87	[5]	M30	T11330	8.01	[5]
A6	T30106	7.84	[5]	M33	T11333	8.03	[5]
A7	T30107	7.66	[5]	M36	T11336	8.18	[5]
A8	T30108	7.89	[5]	M41	T11341	8.17	[32]
A9	T30109	7.78	[5]	M42	T11342	7.81	[5]
A10	T30110	7.68	[32]	M46	T11346	7.83	[32]
				M47	T11347	7.96	[32]
D2	T30402	7.69	[5]	O1	T31501	7.85	[5]
D3	T30403	7.70	[5]	O2	T31502	7.60	[5]
D4	T30404	7.70	[5]	O6	T31506	7.70	[32]
D5	T30405	7.71	[5]	O7	T31507	7.88	[5]
D7	T30407	7.68	[5]				
H10	T20810	7.78	[5]	P2	T51602	7.86	[32]
H11	T20811	7.79	[5]	P5	T51605	7.80	[32]
H12	T20812	7.83	[5]	P6	T51606	7.85	[5]
H13	T20813	7.75	[5]	P20	T51620	7.83	[5]
H14	T20814	7.89	[5]	P21	T51621	7.83	[5]
H19	T20819	7.98	[32]				
				S1	T41901	7.92	[5]
H20	—	8.18	[5]	S2	T41902	7.79	[5]
H21	T20821	8.21	[5]	S4	T41904	7.74	[5]
H22	T20822	8.36	[5]	S5	T41905	7.76	[5]
H26	T20826	8.68	[5]	S6	T41906	7.75	[32]
H42	T20842	8.15	[32]	S7	T41907	7.78	[5]
L2	T61202	7.83	[5]	T1	T12001	8.67	[33]
L3	T61203	7.82	[5]	T2	T12002	8.67	[33]
L6	T61206	7.86	[5]	T4	T12004	8.68	[33]
				T5	T12005	8.75	[5]
M1	T11301	7.89	[33]	T6	T12006	8.89	[33]
M2	T11302	8.16	[33]	T8	T12008	8.43	[32]
M3, class 1	T11313	8.15	[32]	T15	T12015	8.19	[5]
M3, class 2	T11323	8.16	[32]				
M4	T11304	7.97	[5]	W1	T72301	7.84	[33]
M7	T11307	7.94	[5]	W2	T72302	7.81	[5]
M10	T11310	7.88	[33]	W3	—	7.82	[5]
				W7	—	7.85	[5]

TABLE 1.6A Density of nickel-base superalloys at normal temperatures.

Alloy	UNS No.	Density, g/cm^3	Ref.	Alloy	UNS No.	Density, g/cm^3	Ref.
Allcorr	N06110	8.39	[34]	IN-587		8.08	[35]
Alloy No. 230	N06230	8.83	[34]	IN-597		8.04	[35]
Astroloy		7.91	[1]	IN-731		7.75	[37]
D-979	N09979	8.19	[35]	IN-738		8.10	[37]
Hastelloy B	N10001	9.24	[34]	IN-792		8.25	[37]
Hastelloy B-2	N10665	9.22	[34]	IN-853		8.09	[35]
Hastelloy B-3	N10675	9.22	[34]	Incoloy 800	N08800	7.94	[34]
Hastelloy C	N10002	8.94	[36]	Incoloy 800H	N08810	7.94	[34]
Hastelloy C-4	N06455	8.64	[34]	Incoloy 800HT	N08811	7.94	[34]
Hastelloy C-22	N06022	8.69	[34]	Incoloy 804	N06804	7.91	[37]
Hastelloy C-276	N10276	8.87	[34]	Incoloy 825	N08825	8.14	[34]
Hastelloy D		7.77	[37]	Incoloy 840		7.92	[31]
Hastelloy F	N06001	8.17	[21]	Incoloy 901	N09901	8.21	[31]
Hastelloy G	N06007	8.31	[34]	Incoloy DS		7.91	[1]
Hastelloy G-2	N06975	8.17	[34]	Inconel X550		8.30	[21]
Hastelloy G-3	N06985	8.31	[34]	Inconel 597		8.04	[4]
Hastelloy G-30	N06030	8.22	[34]	Inconel 600	N06600	8.41	[37]
Hastelloy H-9M	N06920	8.39	[34]	Inconel 601	N06601	8.05	[37]
Hastelloy N	N10003	8.78	[34]	Inconel 610		8.30	[37]
Hastelloy S	N06635	8.76	[4]	Inconel 617	N06617	8.36	[1]
Hastelloy W	N10004	8.26	[31]	Inconel 625	N06625	8.44	[34]
Hastelloy X	N06002	8.23	[34]	Inconel 671		7.86	[38]
Haynes 20 Mod	N08320	8.05	[34]	Inconel 690	N06690	8.14	[4]
IN-100	N13100	7.74	[37]	Inconel 700		8.16	[31]
IN-102	N06102	8.55	[35]	Inconel 702	N07702	8.02	[31]
IN-162		8.08	[37]	Inconel 705		8.07	[37]

Continues on next page

TABLE 1.6A *continued.*

Alloy	UNS No.	Density, g/cm^3	Ref.
Inconel 706	N09706	8.08	[35]
Inconel 713	N07713	7.91	[35]
Inconel 718	N07718	8.19	[34]
Inconel 722		8.25	[31]
Inconel X750	N07750	8.25	[39]
MAR-M 200		8.41	[37]
MAR-M 246		8.43	[37]
MAR-M 247		8.53	[4]
MAR-M 252	N07252	8.24	[37]
MAR-M 421		8.08	[35]
MAR-M 432		8.16	[35]
Nimocast 75		8.44	[4]
Nimocast 80	N07080	8.17	[39]
Nimocast 90		8.18	[39]
Nimocast 242		8.40	[39]
Nimocast 263		8.36	[39]
Nimocast 713 LC		8.01	[39]
Nimocast 738		8.11	[39]
Nimonic 75	N06075	8.37	[36]
Nimonic 80A	N07080	8.19	[39]
Nimonic 81		8.06	[39]
Nimonic 90	N07090	8.18	[36]
Nimonic 91		8.08	[31]
Nimonic 95		8.06	[36]
Nimonic 100		8.03	[36]
Nimonic 101		8.04	[31]
Nimonic 105		8.01	[39]
Nimonic 115		7.85	[37]
Nimonic 118		7.85	[19]
Nimonic 120		8.02	[39]
Nimonic 263	N07263	8.36	[39]
Nimonic 901	N09901	8.16	[39]
Nimonic 942		8.12	[35]
Nimonic DS		7.91	[36]
Nimonic PK.33		8.21	[35]
Ni Span C-902	N09902	8.10	[1]
Pyromet 600	N06600	8.50	[30]
Pyromet 625	N06625	8.44	[30]
Pyromet 800	N08800	8.03	[30]
Pyromet 860		8.23	[35]
RA-333	N06333	8.24	[31]
Rene 41	N07041	8.24	[37]
Rene 77		7.91	[35]
Rene 80		8.16	[35]
Rene 95		8.23	[35]
Udimet 500	N07500	8.02	[37]
Udimet 520		8.22	[35]
Udimet 700		7.91	[1]
Udimet 710		8.08	[35]
Unitemp AF2-1DA	N07012	7.99	[35]
Waspaloy A	N07001	8.19	[31]

TABLE 1.6B Density of cobalt-base superalloys at normal temperatures.

Alloy	UNS No.	Density, g/cm^3	Ref.
AR-13		8.43	[35]
AR-213		8.51	[35]
AR-215		8.47	[35]
CM-7		9.05	[35]
FSX-414		8.30	[35]
Haynes 188	R30188	9.13	[35]
L-605	R30605	9.13	[40]
MAR-M 302		9.21	[35]
MAR-M 322		8.91	[35]
MAR-M 509		8.85	[35]
MAR-M 918		8.86	[35]
NASA CoWRe		9.59	[35]
S-816	R30816	8.59	[35]
Stellite 6B		8.38	[38]
TD Co		8.61	[35]
UMCo 50		8.06	[35]
WI-52		8.88	[35]
X-40/X-45	R30031	8.60	[35]

TABLE 1.6C Density of iron-base superalloys at normal temperatures.

Alloy	UNS No.	Density, g/cm^3	Ref.
16-25-6		8.07	[40]
A-286	K66286	7.91	[35]
Cond ST		7.92	[40]
Cond. St + A		7.94	[40]
D-979	K66979	8.17	[31]
Discaloy	K66220	7.97	[35]
Haynes 556		8.23	[38]
N-155		8.19	[35]
Nimonic P.E.11		8.02	[39]
Nimonic P.E.16		8.02	[39]
V-57		7.94	[35]
W-545	K66545	7.89	[40]

TABLE 1.7 Theoretical density of ceramics at normal temperatures.[A]

Formula	Crystal Structure	Material	Density, g/cm³	Ref.
Al_2O_3	hexagonal	alumina	3.98	[41]
-do-	cubic	-do-	3.65	[41]
$Al_2O_3 \cdot SiO_2$	orthorhombic	sillimanite	3.23–3.24	[2]
$2Al_2O_3 \cdot 2SiO_2$	orthorhombic	mullite	2.6–3.3	[2]
B_4C		boron carbide	2.51	[2]
BN	cubic	boron nitride	3.49	[2]
-do-	hexagonal	-do-	2.27	[2]
BeO	hexagonal	beryllium oxide	3.01–3.03	[2]
HfC	cubic	hafnium carbide	12.67	[42]
MgO	cubic	magnesia	3.58	[2]
$MgO \cdot Al_2O_3$	cubic	spinel	3.58	[2]
$MoSi_2$	tetragonal	molybdenum disilicide	6.24–6.29	[2]
SiC	cubic	silicon carbide	3.21	[2]
Si_3N_4	hexagonal	silicon nitride	3.18	[43]
SiO_2	amorphous	silica	2.21	[1]
$SiO_2 \cdot ZrO_2$	tetragonal	zircon	4.6	[2]
TiB_2	hexagonal	titanium diboride	4.52	[42]
TiC	cubic	titanium carbide	4.91	[42]
TiO_2	tetragonal	anatase	3.84	[2]
-do-	tetragonal	rutile	4.25	[2]
-do-	orthorhombic	brookite	4.17	[2]
UC	cubic	uranium carbide	13.63	[44]
U_2C_3	cubic	-do-	12.88	[44]
UC_2	tetragonal	-do-	11.68	[44]
UO_2	cubic	uranium oxide	10.95–10.97	[2]
ZrB_2	hexagonal	zirconium diboride	6.09	[42]
ZrO_2	monoclinic	zirconium oxide	5.56	[2]

[A] Actual bulk densities depend on processing parameters.

TABLE 1.8 Density of plastics at normal temperatures.

Material	Density, g / cm^3	Ref.
Cellulose acetate	1.25–1.32	[45]
Cellulose acetate butyrate	1.15–1.22	[45]
Cellulose acetate propionate	1.18–1.22	[45]
Cellulose nitrate	1.40	[46]
Ethyl cellulose	1.10–1.13	[45]
Fluorocarbon perfluoromethoxy (MFA)	2.12–2.17	[45]
Melamine-formaldehyde	1.55	[45]
Perfluoroalkoxy (PFA)-fluorocarbon	2.12–2.17	[45]
Phenol formaldehyde, general purpose	1.40	[46]
heat resistant	1.9	[46]
Phenol furfural	1.4	[46]
Phenylene oxide-based resins	1.06–1.10	[47]
Polyacrylonitrile (PAN)	1.18	[48]
Poly (acrylonitrile butadiene styrene) (ABS)	1.03–1.06	[49]
Polyamides:		
6 Nylon	1.05–1.18	[45]
11 Nylon	1.03–1.06	[45]
12 Nylon	1.00–1.06	[45]
46 Nylon	1.16–1.20	[45]
66 Nylon	1.06–1.16	[45]
69 Nylon	1.07–1.09	[45]
610 Nylon	1.05–1.09	[45]
612 Nylon	1.05–1.07	[45]
Polyaryl ether	1.14	[50]
Polyaryl sulfone	1.36	[50]
Polybutylate terephthalate (PBT)	1.31–1.38	[47]
Polybutylene (PB)	0.905–0.920	[45]
Polycarbonate (PC)	1.17–1.26	[45]
Polychlorotrifluoroethylene (PCTFE)	2.07–2.12	[45]
Polyether sulfone (PE-Sul)	1.37	[50]
Polyethylene (PE)	0.910–0.961	[45]
Polyethylene terephthalate (PET)	1.30–1.41	[47]
Polyimide	1.33–1.42	[45]
Polyketone	1.22–1.24	[45]
Poly(methyl methacrylate) (PMMA)	1.18–1.20	[45]
Polyoxymethylene (POM) (acetal)	1.31–1.44	[45]
Polyphenylene sulfide	1.34	[50]
Polypropylene (PP)	0.90–0.91	[49]
Polystyrene (PS)	1.03–1.06	[49]
syndiotactic	1.05–1.42	[45]
Polysulfone (PSul)	1.24	[49]
Polytetrafluoroethylene (PTFE)	2.12–2.22	[45]

Continues on next page

TABLE 1.8 *continued.*

Material	Density, g/cm^3	Ref.
Polyurethanes, thermoplastic	1.13–1.24	[45]
Poly (vinyl acetate)	1.19	[48]
Polyvinyl carbazole	1.19	[50]
Polyvinyl chloride (PVC), flexible	1.16–1.35	[49]
rigid	1.30–1.58	[49]
Polyvinylidene chloride (PVdC)	1.68–1.75	[45]
Urea formaldehyde	1.5	[46]

TABLE 1.9 Density of selected other materials.

Material	Density, g/cm^3	Ref.
Asphalt	1.1–1.5	[1]
Brick	1.4–2.2	[1]
Concrete[A]	2.4	[51]
Flint	2.63	[1]
Glass		
soda-lime	2.4–2.8	[1]
borosilicate	2.13–2.48	[52]
aluminosilicate	2.52–2.64	[52]
96% silica	2.18	[52]
fused silica	2.20	[52]
Granite	2.64–2.76	[1]
Limestone	2.68–2.76	[1]
Marble	2.6–2.84	[1]
Porcelain	2.3–2.5	[1]
Rubber		
natural	0.93	[47]
synthetic[B]	0.86–0.94	[47]
oil-resistant[C]	1.0–2.0	[47]
Sandstone	2.14–2.36	[1]
Slate	2.6–3.3	[1]
Wood, seasoned		
ash	0.65–0.85	[1]
birch	0.51–0.77	[1]
cedar	0.49–0.57	[1]
cedar, red	0.37	[51]
cherry	0.70–0.90	[1]
fir, Douglas	0.5	[51]
hickory	0.60–0.93	[1]
maple	0.62–0.75	[1]
oak	0.60–0.90	[1]
oak, white	0.8	[51]
pine, white	0.35–0.50	[1]
pine, yellow	0.37–0.60	[1]
poplar	0.35–0.5	[1]
walnut	0.64–0.70	[1]

[A] Stone or gravel aggregate; 6 to 7.5 gal water per sack of cement; 28 days old.

[B] Synthetic natural, styrene butadiene, polybutadiene, butyl, ethylene propylene.

[C] Neoprene, hypolon, nitrile, epichlorohydrin, fluorocarbon, acrylate, urethane, polysulfide, silicone, fluorosilicone.

TABLE 1.10 Conversion factors for mass density.

1 g/cm^3 = 1000 kg/m^3 = 62.4 lb/ft^3

1 kg/m^3 = 0.001 g/cm^3 = 0.0624 lb/ft^3

1 lb/ft^3 = 0.0160 g/cm^3 = 16.0 kg/m^3

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Notes:

2

Ultrasonic Testing

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A. Useful Ultrasonic Equations

Notation

D	Search unit piezoelectric element diameter
F	Search unit lens F-number
f	Ultrasonic wave frequency
N	Near field transition point
T	Transmission coefficient
R	Reflection coefficient
α	Attenuation
ν	Material sound velocity
ν_l	Material longitudinal wave velocity
ν_s	Material shear wave velocity
Z	Acoustic impedance
z_o	Search unit lens nominal focus distance
λ	Ultrasonic wavelength
ρ	Material density

Ultrasonic Wavelength-Frequency Relationship:

$$\lambda = \frac{\nu}{f} \tag{2.1}$$

Acoustic Impedance:

$$Z = \nu\rho \tag{2.2}$$

Transmission Coefficient:

$$T = \frac{4Z_1Z_2}{(Z_1 + Z_2)^2} \tag{2.3}$$

Reflection Coefficient:

$$R = \left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right)^2 \tag{2.4}$$

Search Unit Near Field Transition Point:

$$N = \frac{D^2}{4\lambda} = \frac{D^2 f}{4\nu} \tag{2.5}$$

Snell's Law:

$$\frac{\sin\,\theta_1}{\sin\,\theta_2} = \frac{\nu_1}{\nu_2} \tag{2.6}$$

Included Angle Beam Spread:

$$\theta = 2\,\sin^{-1}\left(\frac{\lambda}{2D}\right) = 2\,\sin^{-1}\left(\frac{\nu}{2Df}\right) \text{ provided } D > 4\lambda \tag{2.7}$$

Spherical Focused Search unit half-amplitude beam width:

$$d_r = 1.02\lambda F = \frac{1.02\lambda z_o}{D} = \frac{1.02\nu z_o}{Df} \tag{2.8}$$

Spherical Focused Search unit half-amplitude depth of focus:

$$d_z = 1.22\lambda\left(\frac{z_o}{D}\right)^2 = 1.22\,\frac{\nu}{f}\left(\frac{z_o}{D}\right)^2 \tag{2.9}$$

Young's Modulus of Elasticity:

$$E = \rho\nu_s^2\,\frac{(3\nu_l^2 - 4\nu_s^2)}{(\nu_t^2 - \nu_s^2)} \tag*{(2.10)$^{\text{A}}$}$$

Bulk Modulus of Elasticity:

$$B = \rho\left(\nu_l^2 - \frac{4}{3}\,\nu_s^2\right) \tag*{(2.11)$^{\text{A}}$}$$

[A] These equations are valid for an isotropic material.

Shear Modulus of Elasticity:

$$G = \rho \nu_s^2 \qquad (2.12)^{\mathrm{A}}$$

Poisson's Ratio:

$$\sigma = \frac{(\nu_l^2 - 2\nu_s^2)}{(2\nu_l^2 - 2\nu_s^2)} \qquad (2.13)^{\mathrm{A}}$$

B. Material Properties

The material properties of a particular material may differ largely from component to component and depend on variables such as material composition, heat treatment, environmental temperature, porosity, etc. The reported velocities are for baseline reference only.

TABLE 2.1 Material properties for metal solids.

Material	Density, ρ (g/cm^3)	Longitudinal Wavespeed,^{A} ν_t (mm/μs)	Shear Wavespeed, ν_s (mm/μs)	Rayleigh Wavespeed,^{B} ν_R (mm/μs)	Longitudinal Acoustic Impedance,^{C} Z (10^5 g/cm^2 s)	Reference^D
Aluminum	2.7	6.32	3.13		17.1	[1]
Aluminum 7075	2.80	6.26	3.07		17.5	[2]
Aluminum 2014	2.80	6.32	3.07		17.8	[3]
Aluminum 2024	2.77	6.37	3.16	2.95	17.6	[3]
Beryllium	1.82	12.9	8.88	7.87	23.5	[1]
Brass	8.56	4.28	2.03		36.6	[1]
Brass, Half Hard	8.10	3.83	2.05		31.0	[3]
Brass, Naval	8.42	4.43	2.12	1.95	37.3	[3]
Bronze, Phosphor	8.86	3.53	2.23	2.01	31.3	[3]
Cadmium	8.64	2.78	1.5		24.0	[1]
Copper	8.93	4.66	2.26	1.93	41.6	[1]
Gallium	5.95	2.74			16.3	[1]
Gold	19.32	3.24	1.20		62.6	[1]
Inconel	8.25	5.72	3.02	2.79	47.2	[1]
Iron	7.7	5.9	3.23	2.79	45.4	[1]
Iron (Cast)	7.8	4.8	2.4		37.4	[1]
Lead	11.4	2.16	0.70	0.63	24.6	[1]
Magnesium	1.74	6.31			11.0	[1]
Manganese	7.39	4.66	2.35		34.4	[1]
Monel	8.83	6.02	2.72	1.96	53.2	[3]
Nickel	8.88	5.63	2.96	2.64	50.0	[1]
Platinum	21.4	3.96	1.67		84.7	[1]
Silver	10.5	3.6	1.59		37.8	[1]
Nickel Silver	8.75	4.62	2.32	1.69	40.4	[3]
German Silver	8.70	4.76			41.4	[3]

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TABLE 2.1 *continued.*

Material	Density, ρ (g/cm^3)	Longitudinal Wavespeed,[A] ν_t (mm/μs)	Shear Wavespeed, ν_s (mm/μs)	Rayleigh Wavespeed,[B] ν_R (mm/μs)	Longitudinal Acoustic Impedance,[C] Z (10^5 g/cm^2 s)	Reference[D]
Alloy Steel, AISI 4340	7.80	5.85	1.28		45.6	[3]
Carbon Steel, AISI 1020	7.71	5.89	3.24		45.4	[3]
Stainless Steel, type 302	8.03	5.66	3.12	3.12	45.5	[3]
Stainless Steel, type 347	7.91	5.74	3.09		45.4	[3]
Stainless Steel, type 410	7.67	7.39	2.99	2.16	56.7	[3]
Stainless Steel, 17-4	7.77	5.89	3.19		45.8	[2]
Tin	7.29	3.32	1.67		24.2	[1]
Titanium	4.5	6.07	3.31		27.3	[1]
Titanium 6A1 4V	4.41	6.09	3.16		26.9	[2]
Tungsten	19.25	5.18	2.87	2.65	99.7	[1]
Uranium	18.9	3.38	1.96		63.9	[1]
Zinc	7.1	4.17	2.41		29.6	[1]

[A] All wavespeeds are expressed in mm/μs for ease of use, since 1/μs equals MHz, a commonly used frequency range in ultrasonic testing.

[B] In the strictest sense, a “Rayleigh wave” refers only to a surface wave propagating along an unloaded medium. Colloquially this term is often used for surface waves in loaded media as well. The difference in wavespeed for the unloaded and fluid-loaded cases could be several percent.

[C] Computed using Eq 1.2 and the stated longitudinal velocity.

[D] Numerals in brackets refer to references listed at the end of the chapter.

TABLE 2.2 Material properties for glass and ceramic solids.

Material	Density, ρ (g/cm^3)	Longitudinal Wavespeed, ν_l (mm/μs)	Shear Wavespeed, ν_s (mm/μs)	Longitudinal Acoustic Impedance, Z (10^5 g/cm^2 s)	Notes	Reference
Alumina (Al_2O_3)	3.95	9.90	5.56	39.1	Fully dense	[4]
Glass, Crown	2.6	5.66	3.52	14.5	Sintered	[1]
Glass, Quartz	2.60	5.57	3.43	14.5		[1]
Glass, Pyrex	2.24	5.64	3.28	12.6		[1]
Sapphire	2.6	9.8		25.5		[1]
Silica (fused)	1.80	5.96		10.7		[1]
Silicon Carbide (SiC)	3.19	12.18	7.68	38.9	Sintered	[1]
Silicon Nitride (Si_2N_3)	3.27	11	6.25	36.0		[1]
Zirconium Oxide (ZrO_2)	6.06	6.99	3.64	42.4	Fully dense	[4]
Zirconium Oxide (ZrO_2)	5.15	1.65	0.91	8.50	Plasma sprayed, 15% porosity by volume	[4]

TABLE 2.3 Material properties for other non-metal solids.

Material	Density, ρ (g/cm^3)	Longitudinal Wavespeed, ν_l (mm/μs)	Shear Wavespeed, ν_s (mm/μs)	Longitudinal Acoustic Impedance, Z (10^5 g/cm^3 s)	Reference
Acrylic	1.2	2.7		3.2	[1]
Lucite	1.15	2.7	1.1	3.1	[1]
Plexiglass (UVA)	1.27	2.76		3.51	[1]
Plexiglass (UVAII)	1.18	2.73	1.43	3.22	[1]
Polyethylene	1.10	2.67		2.94	[1]
Polystyrene	1.10	2.67		2.94	[1]
Poly Vinylidene-Di-Fluoride (PVDF)	1.79	2.3		4.12	[1]
Teflon	2.20	1.35		2.97	[1]

TABLE 2.4 Material properties for liquids.

Material	Density, ρ (g/cm^3)	Longitudinal Wavespeed, ν_l (mm/μs)	Longitudinal Acoustic Impedance, Z (10^5 g/cm^2 s)	Reference
Acetate	0.87	1.17	1.02	[1]
Acetone	0.79	1.17	0.92	[1]
Alcohol (Ethyl)	0.79	1.18	0.93	[1]
Benzene	0.87	1.3	1.13	[1]
Benzol	0.88	1.33	1.17	[1]
Castor Oil	0.97	1.48	1.44	[1]
Diesel Oil		1.25		[1]
Gasoline	0.80	1.25	1.00	[1]
Glycerin	1.26	1.92	2.42	[1]
Kerosene	0.81	1.32	1.07	[1]
Motor Oil (SAE 20)	0.87	1.74	1.51	[1]
Olive Oil	0.95	1.43	1.36	[1]
Paraffin Oil	0.84	1.42	1.19	[1]
Petroleum	0.83	1.29	1.07	[1]
Water (20°C)	1.00	1.48	1.48	[1]
Water (sea)	1.03	1.53	1.58	[1]

TABLE 2.5 Material properties for gases.

Material	Longitudinal Wavespeed, ν_l (mm/μs)	Reference
Air (20°C)	0.344	[1]
Ammonia	0.415	[1]
Argon	0.319	[1]
Carbon Monoxide	0.337	[1]
Carbon Dioxide	0.258	[1]
Chlorine	0.205	[1]
Helium	0.97	[1]
Hydrogen	1.28	[1]
Methane	0.43	[1]
Nitrogen (20°C)	0.35	[1]
Oxygen (20°C)	0.328	[1]

TABLE 2.6 Wavespeed in water as a function of temperature[A] [5].

Temperature, °C	Velocity, mm/μs	Temperature, °C	Velocity, mm/μs	Temperature, °C	Velocity, mm/μs
0	1.403	34	1.518	68	1.555
1	1.408	35	1.520	69	1.555
2	1.413	36	1.522	70	1.555
3	1.417	37	1.524	71	1.555
4	1.422	38	1.526	72	1.555
5	1.426	39	1.527	73	1.555
6	1.431	40	1.529	74	1.555
7	1.435	41	1.531	75	1.555
8	1.439	42	1.532	76	1.555
9	1.444	43	1.534	77	1.555
10	1.448	44	1.535	78	1.555
11	1.452	45	1.537	79	1.555
12	1.455	46	1.538	80	1.555
13	1.459	47	1.539	81	1.555
14	1.463	48	1.541	82	1.554
15	1.466	49	1.542	83	1.554
16	1.470	50	1.543	84	1.554
17	1.473	51	1.544	85	1.553
18	1.476	52	1.545	86	1.553
19	1.480	53	1.546	87	1.552
20	1.483	54	1.547	88	1.552
21	1.486	55	1.548	89	1.551
22	1.489	56	1.549	90	1.551
23	1.492	57	1.549	91	1.550
24	1.494	58	1.550	92	1.550
25	1.497	59	1.551	93	1.549
26	1.500	60	1.551	94	1.548
27	1.502	61	1.552	95	1.548
28	1.505	62	1.552	96	1.547
29	1.507	63	1.553	97	1.546
30	1.509	64	1.553	98	1.545
31	1.512	65	1.554	99	1.544
32	1.514	66	1.554	100	1.543
33	1.516	67	1.554		

[A] Distilled water at atmospheric pressure.

TABLE 2.7 Attenuation in water as a function of frequency.[A]

Frequency, *f* (MHz)	Attenuation, α (dB/cm)	Frequency, *f* (MHz)	Attenuation, α (dB/cm)
1.0	0.0022	26.0	1.4669
2.0	0.0087	27.0	1.5819
3.0	0.0195	28.0	1.7013
4.0	0.0347	29.0	1.8250
5.0	0.0543	30.0	1.9530
6.0	0.0781	31.0	2.0854
7.0	0.1063	32.0	2.2221
8.0	0.1389	33.0	2.3631
9.0	0.1758	34.0	2.5085
10.0	0.2170	35.0	2.6583
11.0	0.2626	36.0	2.8123
12.0	0.3125	37.0	2.9707
13.0	0.3667	38.0	3.1335
14.0	0.4253	39.0	3.3006
15.0	0.4883	40.0	3.4720
16.0	0.5555	41.0	3.6478
17.0	0.6271	42.0	3.8279
18.0	0.7031	43.0	4.0123
19.0	0.7834	44.0	4.2011
20.0	0.8680	45.0	4.3943
21.0	0.9570	46.0	4.5917
22.0	1.0503	47.0	4.7935
23.0	1.1479	48.0	4.9997
24.0	1.2499	49.0	5.2102
25.0	1.3563	50.0	5.4250

[A] Calculated using $\alpha = 2.17 \times 10^{-15} \cdot f^2$ (dB/cm) as reported by Krautkramer [6].

TABLE 2.8 Ultrasonic attenuation in selected materials at selected ultrasonic frequencies [7].

	α (dB/cm)			
Material	1.0 MHz	2.5 MHz	5.0 MHz	10 MHz
Aluminum	<0.01	0.02	0.07	0.26
Glass	0.02	0.06	0.12	0.24
Lucite	1.5	3.5	7	
Quartz, fused		<0.007	0.01	0.02
Air	1.7	11	40	170

TABLE 2.9 Elastic moduli of selected solids.

Material	Young's, *E* (GPa)	Bulk, *B* (GPa)	Shear, *G* (GPA)	Poisson's Ratio, σ [-]	Reference
Aluminum	69		26	0.33	[8]
Aluminum 2014	72.4		28	0.33	[9]
Aluminum 2017	72.4		27	0.33	[9]
Aluminum 2024	72.4		28	0.33	[9]
Aluminum 6061	69		26	0.33	[9]
Aluminum 7075	71.3	74.5	26.5	0.34	[2]
Brass	101		37	0.35	[8]
Copper	110		46	0.35	[8]
Inconel 600	215				[10]
Inconel 907	159				[10]
Magnesium	45		17	0.29	[8]
Magnesium Alloys	45		17	0.35	[9]
Nickel	207		76	0.31	[8]
Steel	207		83	0.27	[8]
Stainless Steel, 17-4	205	164	79	0.292	[2]
Stainless Steel, type 347	195		77	0.27	[9]
Titanium	107		45	0.36	[8]
Titanium, 6A1 4V	116	105	44	0.32	[2]
Titanium Alloys	110		42	0.33	[9]
Tungsten	407		160	0.28	[8]
Zirconia Oxide (ZrO_2), fully dense	211	189	80.3	0.314	[4]
Zirconia Oxide (ZrO_2), plasma sprayed, 15% porosity by volume	10.8	8.4	4.2	0.284	[4]

C. Critical Angles of Refraction

The first critical angle is the angle of incidence onto a material for which longitudinal waves are reflected completely and only shear waves are transmitted through the second medium. Table 2.10 shows the first critical angles for a number of solid mediums for both water / solid and plastic / solid (i.e., as when contact transducer shoes are used) configurations.

TABLE 2.10 First critical angle for selected solids.[A]

Solid Composition	Water / Solid Interface, degrees	Plastic / Solid Interface, degrees
Aluminum	13.5	25.0
Inconel	15.0	27.8
Iron	14.5	26.9
Magnesium	13.6	25.0
Steel 4340	14.7	27.2
Stainless Steel 17-4	14.6	27.0
Titanium	14.1	26.1
Uranium	26.0	52.2

[A] Calculated using Eq 2.6 in the form $\theta_{1c} = \sin^{-1} (\nu_l^{water/plastic} / \nu_s^{solid})$ and the appropriate velocities from Section B.

The second critical angle is the angle of incidence onto a material for which only surface waves exist along the interface between the two media. Table 2.11 shows the second critical angles for a number of solid mediums for both water / solid and plastic / solid (i.e., as when contact transducer shoes are used) configurations.

TABLE 2.11 Second critical angle for selected solids.[A]

Solid Composition	Water / Solid Interface, degrees	Plastic / Solid Interface, degrees
Aluminum	28.2	58.5
Inconel	29.3	62.1
Iron	27.3	55.8
Steel 4340	27.2	55.5
Stainless Steel 17-4	27.6	56.8
Titanium	26.6	53.8
Uranium	49.0	N/A

[A] Calculated using Eq 2.6 in the form $\theta_{2c} = \sin^{-1} (\nu_l^{water/plastic} / \nu_s^{solid})$ and the appropriate velocities from Section B.

D. Search Unit Sound Fields

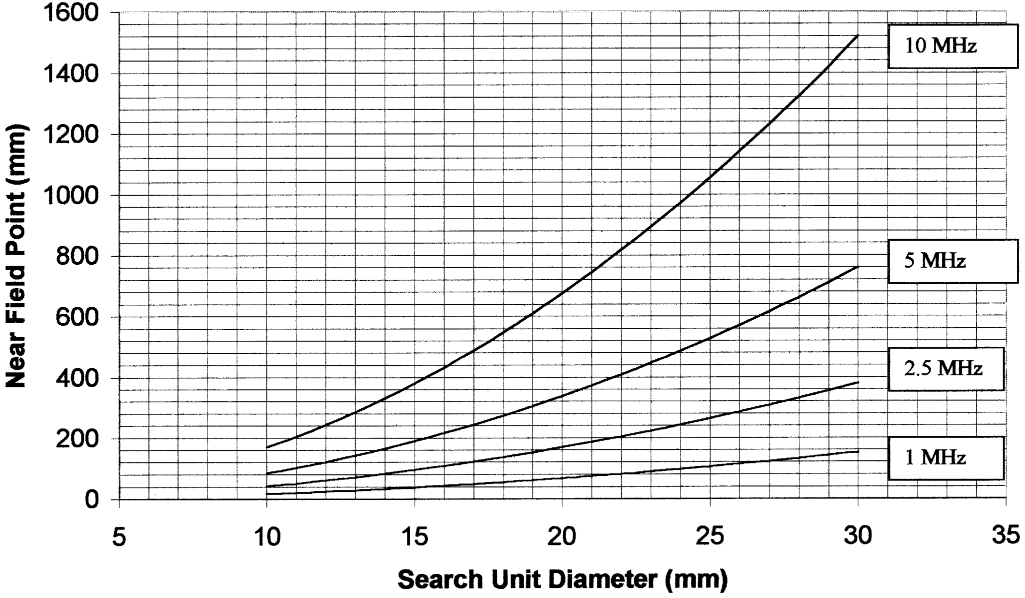

FIG. 2.1 Near field point in water.

Note: The near field transition point N was calculated using Eq 2.5. To find N for other media, use $N_{media} = N_{water} \cdot (\nu_{water} / \nu_{media})$.

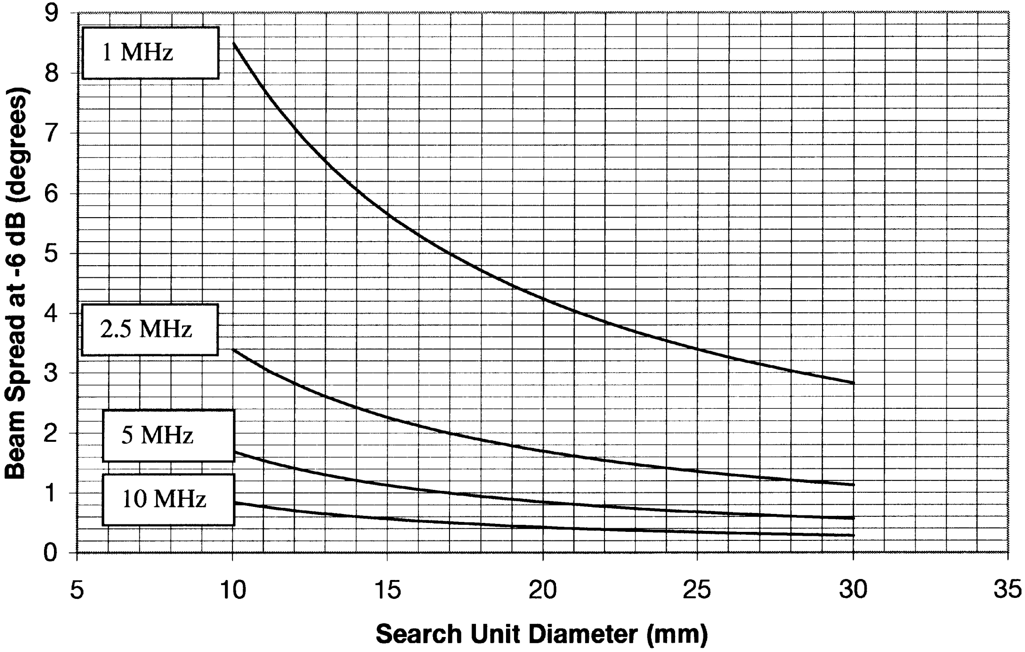

FIG. 2.2 Included angle beam spread in water. Beam spread in other media can be calculated using Eq 2.7.

E. Properties of Crystalline and Ceramic Piezoelectrics

TABLE 2.12 Properties of crystalline and ceramic piezoelectrics [11].

Material	Longitudinal Wavespeed, ν_l (mm/μs)	Dielectric Constant	d_{33} (10^{-12} M/V)	g_{33} (10^{-3} VM/N)	Frequency Constant, (Hz-M)	Density, ρ (g/cm^3)	Longitudinal Acoustic Impedance, Z (10^5 g/cm^2 s)
Barium Titanate	5.64	1200	149	14.1	2740	5.55	31.3
PZT-2	4.41	450	152	38.1	2090	7.6	33.5
PZT-4	4.60	1300	289	26.1	2000	7.5	34.5
PZT-5A	4.35	1700	380	24.8	1890	7.75	33.7
PZT-5H	4.56	3400	593	19.7	2000	7.5	34.2
Lead Metaniobate K-81	3.05	300	85	32	1524	6.2	18.9
Lead Metaniobate K-83	5.48	175	65	42	2743	4.5	24.7
Lead Metaniobate K-85	3.35	80	180	27	1676	5.7	19.1
PVDF[A]	2.20	12	33	339	1100	1.78	3.9
Quartz	5.66	4.5	2.3	NA	2830	6.82	38.6

[A] See Table 2.3 for comparison.

References

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11. http://www.cnde.iastate.edu/cnde/ut_material_properties/Piezoelectrics.html

Notes:

3

Radiography

A. Energy Sources

In the generation of **X-rays** with an X-ray tube, the minimum wavelength λ_{min} that is produced is given by

$$\lambda_{\text{min}} = hc / eV \tag{3.1}$$

where h = Planck's constant, 6.6261×10^{-34} J·s,
c = speed of light, 2.9979×10^{8} m / s,
e = elementary charge, 1.6022×10^{-19} C, and
V = the tube voltage.

Therefore,

$$\lambda_{\text{min}} = 1240 / V \text{ nm} \tag{3.2}$$

The wavelength of maximum X-ray emission λ_{peak} is approximately 3 / 2 times the minimum wavelength. That is,

$$\lambda_{\text{peak}} \approx 1860 / V \text{ nm} \tag{3.3}$$

Table 3.1 lists λ_{min} and λ_{peak} as functions of V.

Characteristics of several **gamma-ray** sources used for radiology are provided in Table 3.2.

TABLE 3.1 Minimum wavelength and wavelength of maximum X-ray emission as functions of tube voltage.

Tube Voltage, kV	Minimum Wavelength, nm	Wavelength of Maximum Emission,[A] nm
50	0.0248	0.0372
100	0.0124	0.0186
150	0.00827	0.0124
200	0.00620	0.00930
300	0.00413	0.00620
400	0.00310	0.00465
500	0.00248	0.00372
1000	0.00124	0.00186
2000	0.000620	0.000930
4000	0.000310	0.000465
6000	0.000207	0.000310
10000	0.000124	0.000186
15000	0.0000827	0.000124
30000	0.0000413	0.0000620

[A] Approximate, per equation (3.3).

TABLE 3.2 Characteristics of some gamma-ray sources [1,2].[A]

Isotope	Half-Life	Gamma-Ray Energy, MeV	Dosage Rate	
			R/Ci-h at 1 m	R/Ci-h at 1 ft
Cesium 137	30 y	0.662	0.32	3.4
Cobalt 60	5.27 y	1.17, 1.33	1.30	14.0
Iridium 192	74 d	0.216 to 0.612	0.48	5.2
Radium 226	1622 y	0.047 to 2.4	0.825	8.88
Selenium 75	120 d	0.066 to 0.401	0.203	2.18
Thulium 170	128 d	0.052, 0.084	0.025	0.27
Ytterbium 169	32 d	0.063 to 0.308	0.125	1.34

[A] Numerals in brackets designate references listed at the end of the chapter.

B. Absorption/Attenuation

The basic law of X-ray absorption is given by

$$I_x = I_0 e^{-\mu x} \tag{3.4}$$

where x is the thickness of the material, I_0 is the incident intensity of radiation, I_x is the transmitted intensity, and μ is the *linear* *absorption coefficient.* Its value depends on the material and the X-ray wavelength. Values of μ are listed in Tables 3.3a, 3.3b, 3.3c, and 3.3d for various elements and wavelengths.

Table 3.4 lists the approximate radiographic absorption equivalence of several metals relative to steel.

For a *half-value layer thickness* (HVL)

$$I_x / I_0 = e^{-\mu x} = 1/2 \tag{3.5}$$

and

$$X_{\mathrm{HVL}} = 0.693/\mu \tag{3.6}$$

Similarly, for a *tenth-value layer thickness* (TVL)

$$X_{\mathrm{TVL}} = 2.303/\mu \tag{3.7}$$

and for a given wavelength

$$X_{\mathrm{TVL}} = 3.32 X_{\mathrm{HVL}} \tag{3.8}$$

Half- and tenth-value layer thicknesses for concrete, lead, and steel are given in Table 3.5 as a function of energy level.

The *mass absorption coefficient, k,* is given by

$$k = \mu/\rho \tag{3.9}$$

where ρ is the density of the material. Densities of materials are tabulated in Chapter 1.

TABLE 3.3a Linear attenuation coefficients of selected elements, cm^{-1}.

Energy, kV	Aluminum (Z = 13)	Antimony (Z = 51)	Barium (Z = 56)	Beryllium (Z = 4)	Cadmium (Z = 48)	Calcium (Z = 20)	Carbon (Z = 6)
50	0.964	72.8	51.8	0.280	82.5	1.54	0.413
100	0.459	11.6	8.16	0.242	13.1	0.399	0.340
150	0.373	4.06	2.87	0.217	4.77	0.257	0.300
200	0.329	2.22	1.51	0.198	2.63	0.211	0.273
300	0.281	1.10	0.703	0.172	1.35	0.172	0.238
400	0.250	0.768	0.469	0.155	0.969	0.151	0.212
500	0.228	0.616	0.366	0.141	0.793	0.136	0.194
1000	0.166	0.380	0.219	0.103	0.501	0.0981	0.141
2000	0.116	0.271	0.153	0.0717	0.357	0.0695	0.0986
4000	0.0837	0.236	0.136	0.0484	0.308	0.0521	0.0677
6000	0.0718	0.239	0.139	0.0386	0.310	0.0465	0.0546
10000	0.0621	0.257	0.152	0.0295	0.331	0.0431	0.0433
15000	0.0586	0.286	0.169	0.0246	0.365	0.0436	0.0375
30000	0.0589	0.347	0.209	0.0198	0.442	0.0465	0.0324

TABLE 3.3b Linear attenuation coefficients of selected elements, cm^{-1}.

Energy, kV	Chromium ($Z = 24$)	Cobalt ($Z = 27$)	Copper ($Z = 29$)	Iron ($Z = 26$)	Lead ($Z = 82$)	Magnesium ($Z = 12$)	Manganese ($Z = 25$)
50	11.0	18.8	22.9	15.2	65.0	0.561	12.6
100	2.29	3.53	4.10	2.93	62.0	0.292	2.52
150	1.29	1.80	1.98	1.54	21.8	0.242	1.36
200	0.992	1.32	1.39	1.15	10.7	0.216	1.03
300	0.769	0.970	0.997	0.866	4.29	0.186	0.788
400	0.662	0.827	0.837	0.740	2.49	0.165	0.679
500	0.595	0.740	0.742	0.662	1.72	0.150	0.608
1000	0.426	0.525	0.524	0.471	0.798	0.109	0.435
2000	0.302	0.374	0.374	0.334	0.524	0.0768	0.309
4000	0.232	0.291	0.295	0.260	0.484	0.0548	0.238
6000	0.212	0.271	0.277	0.239	0.505	0.0467	0.219
10000	0.202	0.264	0.272	0.233	0.570	0.0399	0.211
15000	0.209	0.275	0.285	0.241	0.643	0.0374	0.217
30000	0.231	0.311	0.327	0.270	0.807	0.0369	0.243

TABLE 3.3c Linear attenuation coefficients of selected elements, cm^{-1}.

Energy, kV	Molybdenum ($Z = 42$)	Nickel ($Z = 28$)	Niobium ($Z = 41$)	Selenium ($Z = 34$)	Silicon ($Z = 14$)	Silver ($Z = 47$)	Tantalum ($Z = 73$)
50	69.9	21.5	55.0	18.0	1.00	96.7	71.4
100	11.1	3.96	8.83	3.03	0.428	15.3	69.7
150	4.26	1.96	3.44	1.30	0.338	5.60	24.4
200	2.47	1.40	2.00	0.827	0.298	3.11	12.2
300	1.41	1.03	1.16	0.548	0.254	1.63	5.01
400	1.06	0.865	0.883	0.448	0.226	1.17	3.02
500	0.897	0.769	0.756	0.389	0.205	0.967	2.16
1000	0.593	0.543	0.500	0.269	0.149	0.621	1.08
2000	0.422	0.389	0.357	0.192	0.105	0.440	0.730
4000	0.357	0.304	0.300	0.155	0.0757	0.378	0.674
6000	0.351	0.283	0.294	0.150	0.0660	0.379	0.702
10000	0.367	0.279	0.308	0.152	0.0576	0.404	0.785
15000	0.402	0.291	0.336	0.162	0.0550	0.445	0.890
30000	0.479	0.331	0.398	0.189	0.0555	0.538	1.11

TABLE 3.3d Linear attenuation coefficients of selected elements, cm^{-1}.

Energy, kV	Tin ($Z = 50$)	Titanium ($Z = 22$)	Tungsten ($Z = 74$)	Uranium ($Z = 92$)	Vanadium ($Z = 23$)	Zinc ($Z = 30$)	Zirconium ($Z = 40$)
50	76.7	5.40	82.1	146.0	7.87	20.0	38.9
100	12.0	1.24	81.5	23.6	1.72	3.56	6.26
150	4.37	0.749	28.2	46.6	1.00	1.67	2.46
200	2.37	0.595	14.0	22.4	0.781	1.15	1.46
300	1.19	0.472	5.80	8.90	0.614	0.813	0.855
400	0.840	0.412	3.44	5.11	0.534	0.677	0.666
500	0.675	0.371	2.45	3.48	0.481	0.601	0.561
1000	0.419	0.266	1.22	1.46	0.346	0.423	0.378
2000	0.299	0.189	0.821	0.913	0.244	0.302	0.270
4000	0.260	0.144	0.759	0.842	0.187	0.239	0.225
6000	0.262	0.130	0.797	0.881	0.170	0.225	0.221
10000	0.283	0.122	0.894	0.989	0.162	0.223	0.230
15000	0.313	0.124	1.00	1.13	0.164	0.235	0.249
30000	0.382	0.136	1.26	1.41	0.181	0.270	0.296

TABLE 3.4 Approximate radiographic absorption equivalence for several metals relative to steel[A] (ASTM E 94[B]) [3].

	Energy Level, X-Rays									Gamma Rays		
Metal	50 kV	100 kV	150 kV	220 kV	250 kV	400 kV	1 MV	2 MV	4 to 25 MV	Ir 192	Cs 137	Co 60
Magnesium	0.03	0.05	0.05	0.08								
Aluminum	0.06	0.08	0.12	0.18		0.22				0.35	0.35	0.35
Aluminum alloy		0.10	0.14	0.18						0.35	0.35	0.35
Titanium			0.54	0.54		0.71	0.9	0.9	0.9	0.9		0.9
Iron/Steel	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Copper	1.3	1.5	1.6	1.4	1.4	1.4	1.1	1.1	1.2	1.1	1.1	1.1
Zinc			1.4	1.3		1.3			1.2	1.1	1.0	1.0
Brass			1.4	1.3		1.3	1.2	1.1	1.0	1.1	1.1	1.0
Inconel X			1.4	1.3		1.3	1.3	1.3	1.3	1.3	1.3	1.3
Monel		1.7		1.2								
Zirconium		2.4	2.3	2.0	1.7	1.5	1.0	1.0	1.0	1.2		1.0
Lead		14.0	14.0	12.0			5.0	2.5	2.7	4.0	3.2	2.3
Hafnium				14.	12.	9.0	3.0					
Uranium				20.	16.	12.	4.0		3.9	12.6	5.6	3.4

[A] Example: At 220 kV, 1 cm of lead is equivalent to 12 cm of steel in absorption.

[B] ASTM standards referenced herein are cited at the end of the chapter.

TABLE 3.5 Half- and tenth-value layer thicknesses for concrete, steel, and lead (ASTM E 94) [2–4].

	Half-Value Layer, mm			Tenth-Value Layer, mm		
Energy[A]	Concrete	Steel	Lead	Concrete	Steel	Lead
50 kV	4.32		0.05	15.1		0.16
70 kV	8.38		0.15	27.95		0.5
100 kV	15.1	1.5	0.24	50.8	5.0	0.8
125 kV	20.3	2.5	0.27	66.0	8.3	0.9
150 kV	22.35	3.6	0.29	73.6	12.	0.95
200 kV	25.4	5.1	0.48	83.8	17.	1.6
250 kV	27.95	6.4	0.9	94.0	21.	3.0
300 kV	31.2	6.9	1.4	104.0	23.	4.6
400 kV	33.0	8.9	2.2	109.1	30.	7.3
500 kV	35.55		3.6	116.8		11.9
Ir 192	41.	13.	6.1	140.	43.	20.
Cs 137	48.		6.35	160.		21.
1 MV	44.45	14.5	7.9	147.1	48.	26.0
2 MV	63.5	20.3	12.7	210.4	67.	42.0
Co 60	66.	22.	12.4	220.	73.	41.
3 MV	73.6		14.7	241.2		48.5
4 MV	91.4	25.4	16.5	304.5	84.	54.8
6 MV	104.0	29.2	17.0	348.0	97.	56.6
10 MV	116.8	31.8	16.5	388.5	106.	55.0
16 MV		33.0			110.	
20 MV		38.			130.	

[A] Approximate values determined at high filtration.

C. Geometric Unsharpness

$$U_g = F(t/d_0) \tag{3.10}$$

where U_g = geometric unsharpness, mm (in.),
F = focal spot size, mm (in.),
t = specimen-to-film distance, measured from the source side of the specimen, mm (in.), and
d_0 = source-to-specimen distance, mm (in.)

Values of geometric unsharpness U_g may be determined from the nomograms in Figs. 3.1a and 3.1b.

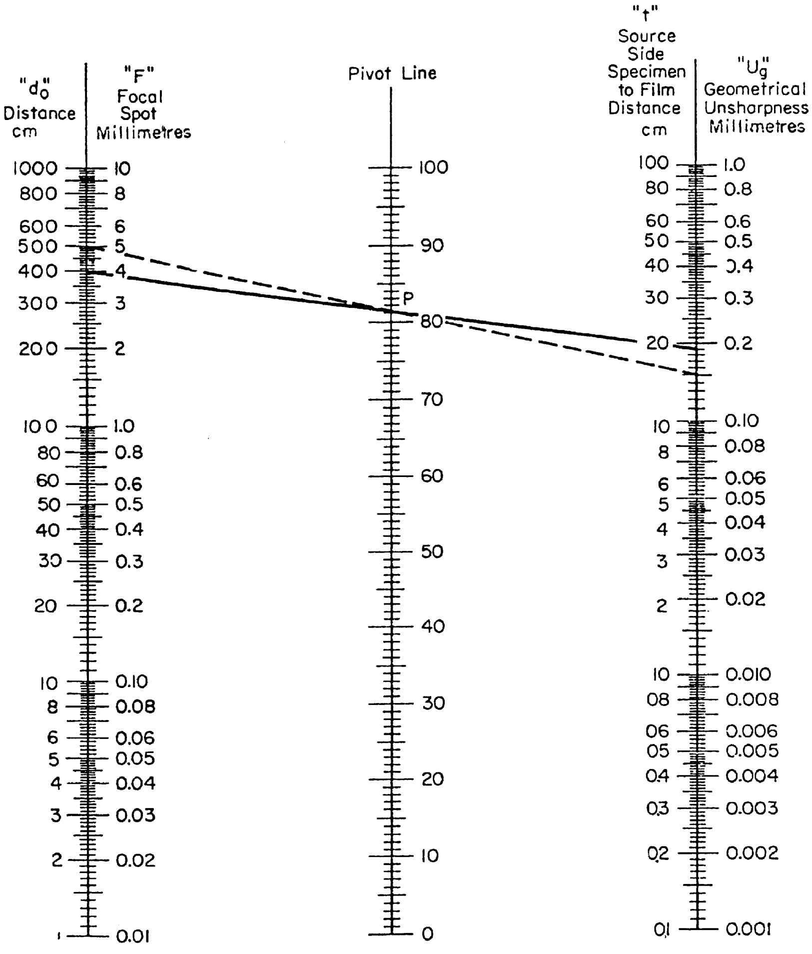

FIG. 3.1a Nomogram for determining geometrical unsharpness in metric units (ASTM E 94).

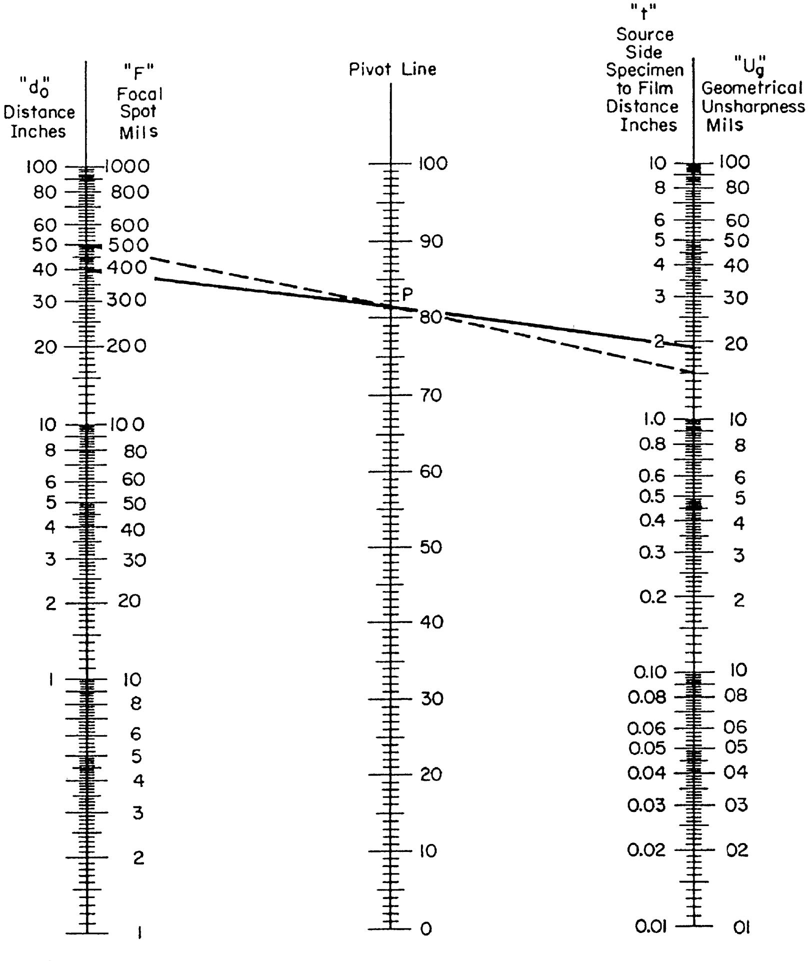

FIG. 3.1b Nomogram for determining geometrical unsharpness in inches (ASTM E 94).

Unless otherwise specified, geometric unsharpness should not exceed the following values (ASTM E 1032 and E 1416).

TABLE 3.6 Maximum geometric unsharpness.

Material Thickness	Max U_g, in. (mm)
Under 2 in. (50 mm)	0.020 (0.50)
2 through 3 in. (50 through 75 mm)	0.030 (0.75)
Over 3 through 4 in. (75 through 100 mm)	0.040 (1.00)
Over 4 in. (100 mm)	0.070 (1.75)

The source-to-film distance, *SFD,* is given by

$$SFD = d_0 + t = (FT / U_g) + t \tag{3.11}$$

Calculate the minimum allowable source-to-film distance using the following values of U_g as a minimum (ASTM E 1742).

TABLE 3.7 Minimum allowable source-to-film distance.

Material Thickness, mm	U_g, mm
0 to 51	0.51
51 through 102	0.76
Over 102	1.02

With gamma-ray radiography the energy cannot be adjusted to accommodate material thickness. Rather, it is necessary to change the source to one that emits rays of more suitable energy. Table 3.8 provides a guide for steel.

TABLE 3.8 Suitable gamma-ray sources for various steel thicknesses [5].

	High-Sensitivity Technique		Low-Sensitivity Technique	
Source	mm	in.	mm	in.
Ir-192	18 to 80	0.7 to 3	6 to 100	0.25 to 4
Cs-137	30 to 100	1.2 to 4	20 to 120	0.8 to 5
Co-60	50 to 150	2 to 6	30 to 200	1.2 to 8
Yb-169	2 to 12	0.08 to 0.5	1 to 15	0.04 to 0.6
Tm-170	2 to 12	0.08 to 0.5	1 to 15	0.04 to 0.6

D. Exposure

$$E = mt \tag{3.12}$$

where E = exposure
m = tube current for X-rays, or source activity in curies for gamma rays, and
t = time.

This equation expresses the *reciprocity law,* that is, for a given exposure the tube current (or the source activity) and the time of exposure are inversely related. This law applies for direct X-ray (or gamma-ray) and lead screen exposures. However, when exposures are made with fluorescent intensifying screens, the law is not quite accurate. An example of the *failure of the reciprocity law* is given in Table 3.9.

Amount of enlargement is given by

$$S_o / S_i = D_o / D_i \tag{3.13}$$

TABLE 3.9 Example of reciprocity law failure with use of fluorescent intensifying screens.[A]

Change in: tube current, m_2/m_1, or intensity, I_2/I_1	Corresponding change in exposure time according to the reciprocity law, $(t_2/t_1)_{\text{predicted}}$	Approximate actual change in exposure time to achieve equal exposure, $(t_2/t_1)_{\text{actual}}$
4.0	0.25	0.1
2.2	0.45	0.2
1.6	0.63	0.5
1.0	1.0	1.0
0.63	1.6	2.0
0.45	2.2	4.0
0.25	4.0	8.0

[A] Based on data in [3].

where S_o = object size,
S_i = image size,
D_o = object-to-source distance, and
D_i = image-to-source distance.

The *inverse square law* is given by

$$I_1 / I_2 = (D_2)^2 / (D_1)^2 \tag{3.14}$$

where I = intensity, and
D = distance.

A tabulation of the inverse square law for selected distances is given in Table 3.10.

TABLE 3.10 Inverse square law[A]: Ratio of intensities I_2/I_1.

D_1, cm	D_2, cm 50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
50	1.00	0.69	0.51	0.39	0.31	0.25	0.21	0.17	0.15	0.13	0.11	0.10	0.09	0.08	0.07	0.06
60	1.44	1.00	0.73	0.56	0.44	0.36	0.30	0.25	0.21	0.18	0.16	0.14	0.12	0.11	0.10	0.09
70	1.96	1.36	1.00	0.77	0.60	0.49	0.40	0.27	0.29	0.25	0.22	0.19	0.17	0.15	0.14	0.12
80	2.56	1.78	1.31	1.00	0.79	0.64	0.53	0.44	0.38	0.33	0.28	0.25	0.22	0.20	0.18	0.16
90	3.24	2.25	1.65	1.27	1.00	0.81	0.67	0.56	0.48	0.41	0.36	0.32	0.28	0.25	0.22	0.20
100	4.00	2.78	2.04	1.56	1.23	1.00	0.82	0.69	0.59	0.51	0.44	0.39	0.35	0.31	0.28	0.25
110	4.84	3.36	2.47	1.89	1.49	1.21	1.00	0.84	0.72	0.62	0.54	0.47	0.42	0.37	0.34	0.28
120	5.76	4.00	2.94	2.25	1.78	1.44	1.19	1.00	0.85	0.73	0.64	0.56	0.50	0.44	0.40	0.36
130	6.76	4.69	3.45	2.64	2.09	1.69	1.40	1.17	1.00	0.86	0.75	0.66	0.58	0.52	0.47	0.42
140	7.84	5.44	4.00	3.06	2.42	1.96	1.62	1.36	1.16	1.00	0.87	0.77	0.68	0.60	0.54	0.49
150	9.00	6.25	4.59	3.52	2.78	2.25	1.86	1.56	1.33	1.15	1.00	0.88	0.78	0.69	0.62	0.56
160	10.24	7.11	5.22	4.00	3.16	2.56	2.12	1.80	1.51	1.31	1.14	1.00	0.86	0.79	0.71	0.64
170	11.56	8.03	5.90	4.52	3.21	2.89	2.39	2.01	1.71	1.47	1.28	1.85	1.00	0.89	0.80	0.72
180	12.96	9.00	6.61	5.06	4.00	3.24	2.68	2.25	1.92	1.65	1.44	1.27	1.12	1.00	0.90	0.81
190	14.44	10.02	7.37	5.64	4.46	3.61	2.98	2.51	2.14	1.84	1.60	1.41	1.25	1.11	1.00	0.90
200	16.00	11.11	8.26	6.25	4.94	4.00	3.31	2.78	2.37	2.04	1.78	1.56	1.38	1.23	1.11	1.00

[A] Example: If $D_1 = 80$ cm and $D_2 = 150$ cm, then $I_2/I_1 = 0.28$.

E. Quality/Sensitivity

Typical image quality levels using *hole-type IQIs* are as follows (ASTM E 1025):

TABLE 3.11 Typical image quality levels.

Image Quality Levels	IQI Thickness	Minimum Perceptible Hole Diameter	Equivalent IQI Sensitivity, %[A]
Standard image quality levels			
2-1T	2% of specimen	1T	1.4
2-2T	2% of specimen	2T	2.0
2-4T	2% of specimen	4T	2.8
Special image quality levels			
1-1T	1% of specimen	1T	0.7
1-2T	1% of specimen	2T	1.0
4-2T	4% of specimen	2T	4.0

[A] Equivalent IQI sensitivity is that thickness of the IQI, expressed as a percentage of the part thickness, in which the 2T hole would be visible under the same conditions.

Equivalent IQI (*penetrameter*) *sensitivity* (EPS) may be calculated with the following relation (using consistent inch or millimeter units)

$$\alpha = (100/X)\,(TH/2)^{1/2} \tag{3.15}$$

where α = equivalent IQI sensitivity, %,
X = section thickness to be examined,
T = IQI thickness, and
H = hole diameter.

Alternatively, calculate the percentages

$$A = 100T/X \text{ and } B = 100H/X \tag{3.16}$$

Then proceed to the nomograph in Fig. 3.2 and draw a line joining the A value and the B value. Read the EPS value, in percent, off the center scale where the line crosses it.

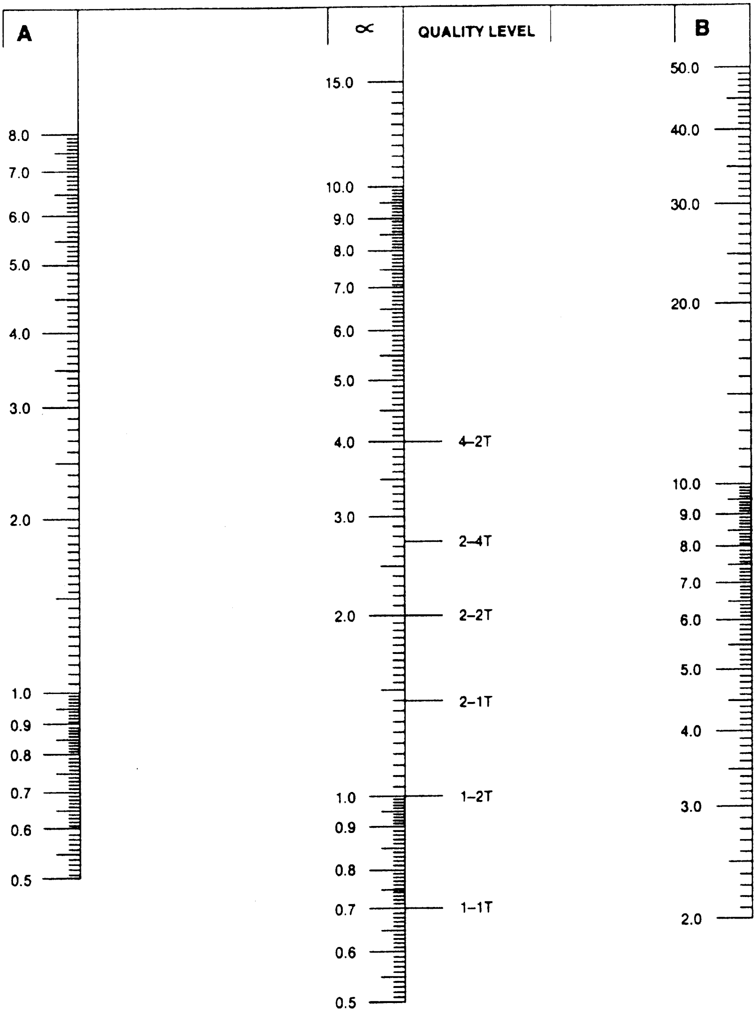

FIG. 3.2 Equivalent IQI (penetrameter) sensitivity nomograph (ASTM E 1025).

Table 3.12 provides a list of various hole-type image quality indicators (IQIs) and the diameters of wires of corresponding equivalent penetrameter sensitivity (EPS) with the applicable 1T, 2T, and 4T holes in the plaque.

TABLE 3.12 Wire sizes equivalent to corresponding 1T, 2T, and 4T holes in various hole-type plaques (ASTM E 747).

Plaque Thickness, in. (mm)	Plaque IQI Identification Number	Diameter of Wire with EPS of Hole in Plaque, in. (mm)		
		1T	2T	4T
0.005 (0.13)	5		0.0038 (0.09)	0.006 (0.15)
0.006 (0.16)	6		0.004 (0.10)	0.0067 (0.18)
0.008 (0.20)	8	0.0032 (0.08)	0.005 (0.13)	0.008 (0.20)
0.009 (0.23)	9	0.0035 (0.09)	0.0056 (0.14)	0.009 (0.23)
0.010 (0.25)	10	0.004 (0.10)	0.006 (0.15)	0.010 (0.25)
0.012 (0.30)	12	0.005 (0.13)	0.008 (0.20)	0.012 (0.28)
0.015 (0.38)	15	0.0065 (0.16)	0.010 (0.25)	0.016 (0.41)
0.017 (0.43)	17	0.0076 (0.19)	0.012 (0.28)	0.020 (0.51)
0.020 (0.51)	20	0.010 (0.25)	0.015 (0.38)	0.025 (0.63)
0.025 (0.64)	25	0.013 (0.33)	0.020 (0.51)	0.032 (0.81)
0.030 (0.76)	30	0.016 (0.41)	0.025 (0.63)	0.040 (1.02)
0.035 (0.89)	35	0.020 (0.51)	0.032 (0.81)	0.050 (1.27)
0.040 (1.02)	40	0.025 (0.63)	0.040 (1.02)	0.063 (1.57)
0.050 (1.27)	50	0.032 (0.81)	0.050 (1.27)	0.080 (2.03)
0.060 (1.52)	60	0.040 (1.02)	0.063 (1.57)	0.100 (2.54)
0.070 (1.78)	70	0.050 (1.27)	0.080 (2.03)	0.126 (3.20)
0.080 (2.03)	80	0.063 (1.57)	0.100 (2.54)	0.160 (4.06)
0.100 (2.5)	100	0.080 (2.03)	0.126 (3.20)	0.200 (5.08)
0.120 (3.05)	120	0.100 (2.54)	0.160 (4.06)	0.250 (6.35)
0.140 (3.56)	140	0.126 (3.20)	0.200 (5.08)	0.320 (8.13)
0.160 (4.06)	160	0.160 (4.06)	0.250 (6.35)	
0.200 (5.08)	200	0.200 (5.08)	0.320 (8.13)	
0.240 (6.10)	240	0.250 (6.35)		
0.280 (7.11)	280	0.320 (8.13)		

Other equivalencies between wire- and hole-type IQIs may be calculated with the relation

$$F^3 d^3 l = T^2 H^2 (\pi/4) \qquad (3.17)$$

where F = form factor for wire, 0.79,
d = wire diameter, mm (in.)
l = effective length of wire, 7.6 mm (0.3 in.),

T = plaque thickness, mm (in.), and
H = diameter of hole, mm (in.).

Figures 3.3 and 3.4 are conversion charts for hole-type IQIs containing 1T and 2T holes to wires. The sensitivities are given as a percentage of the specimen thickness.

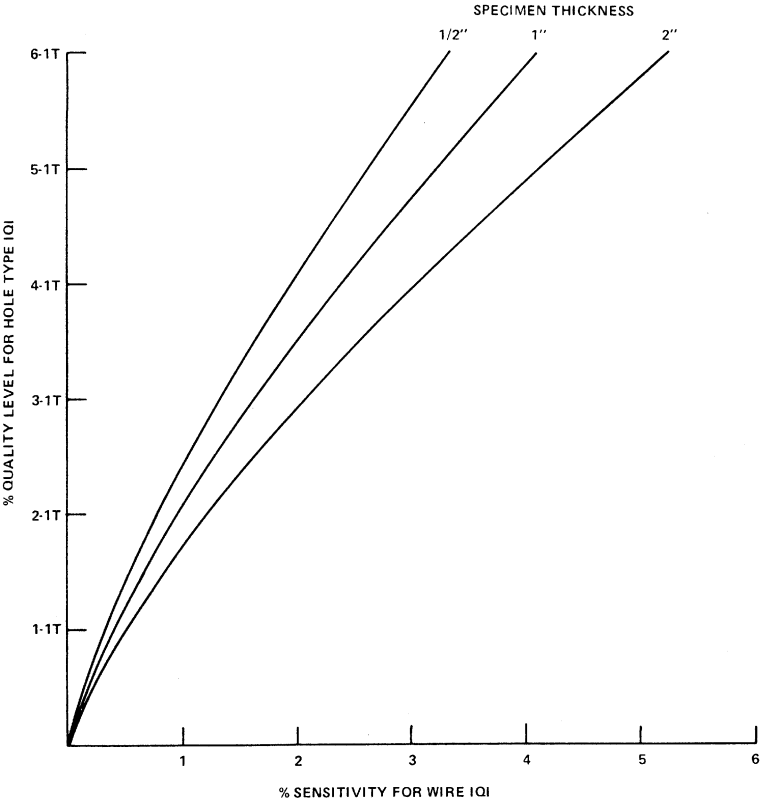

FIG. 3.3 Conversion chart for 1T quality level holes to % wire sensitivity (ASTM E 747).

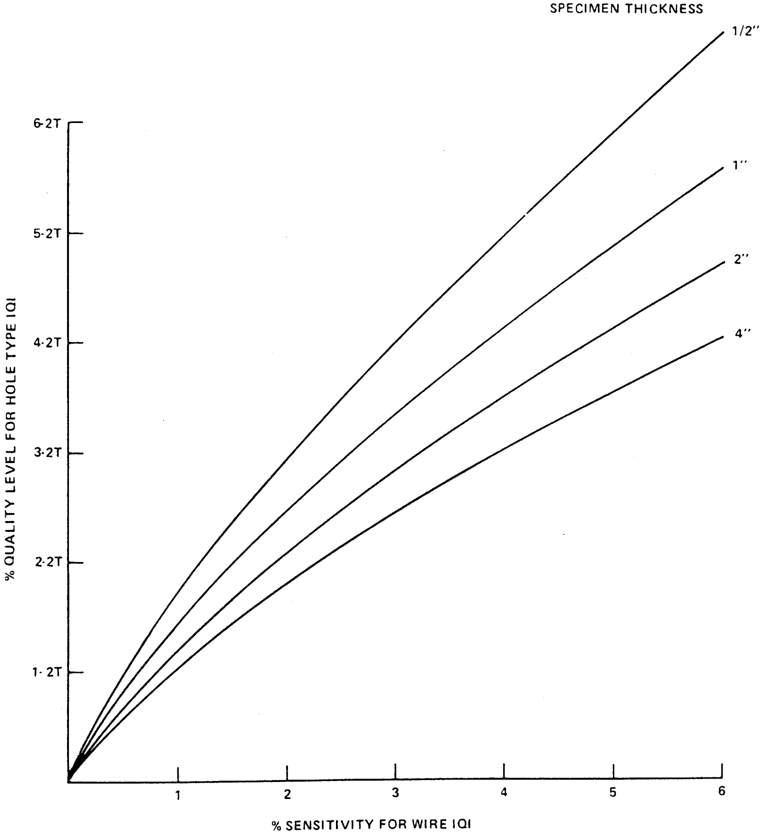

FIG. 3.4 Conversion chart for 2T quality level holes to % wire sensitivity (ASTM E 747).

Wires are generally available only in discrete sizes as listed in Table 3.13.

TABLE 3.13 Standard wire gages.

	AWG/B&S Gage for Nonferrous Wire		USA Steel Wire Gage	
Gage No.	mm	in.	mm	in.
00	9.27	0.365	8.41	0.331
0	8.25	0.325	7.79	0.306
1	7.35	0.289	7.19	0.283
2	6.54	0.258	6.65	0.262
3	5.83	0.229	6.19	0.244
4	5.19	0.204	5.72	0.225
5	4.62	0.182	5.26	0.207
6	4.11	0.162	4.88	0.192
7	3.67	0.144	4.50	0.177
8	3.26	0.128	4.11	0.162
9	2.91	0.114	3.77	0.143
10	2.59	0.102	3.43	0.135
11	2.30	0.091	3.06	0.120
12	2.05	0.081	2.68	0.106
13	1.83	0.072	2.32	0.092
14	1.63	0.064	2.03	0.080
15	1.45	0.057	1.83	0.072
16	1.29	0.051	1.59	0.062
17	1.15	0.045	1.37	0.054
18	1.02	0.040	1.21	0.048
19	0.91	0.036	1.04	0.041
20	0.81	0.032	0.88	0.035
21	0.72	0.028	0.81	0.032
22	0.64	0.025	0.73	0.029
23	0.57	0.023	0.66	0.026
24	0.51	0.020	0.58	0.023
25	0.45	0.018	0.52	0.020
26	0.40	0.016	0.46	0.018
27	0.36	0.014	0.44	0.017
28	0.32	0.013	0.41	0.016
29	0.29	0.011	0.38	0.015
30	0.25	0.010	0.36	0.014
31	0.23	0.0089	0.34	0.0132
32	0.20	0.0080	0.33	0.0128
33	0.18	0.0071	0.30	0.0118
34	0.16	0.0063	0.26	0.0104
35	0.14	0.0056	0.24	0.0095
36	0.13	0.0050	0.23	0.0090
37	0.11	0.0045	0.22	0.0085
38	0.10	0.0040	0.20	0.0080
39	0.09	0.0035	0.19	0.0075
40	0.08	0.0031	0.18	0.0070

The proper *contrast sensitivity gages* (ASTM E 1647) to be used with various material thicknesses are given in Table 3.14.

TABLE 3.14 Contrast sensitivity gage application.

Gage Size	Use on Thicknesses
1	Up to 1.5 in. (38 mm)
2	Over 1.5 in. (38 mm) to 3.0 in. (76 mm)
3	Over 3.0 in. (76 mm) to 6.0 in. (152 mm)
4	Over 6.0 in. (152 mm)

F. Screens

Recommended lead screen thicknesses (ASTM E 1742) are as shown here:

TABLE 3.15 Lead screen thicknesses.

kV Range	Front Screen Maximum, in.	Back Screen Minimum, in.
0 to 150 kV	0.000	0.005 (0.13 mm)
150 to 200 kV and Ir 192	0.005 (0.13 mm)	0.005 (0.13 mm)
200 kV to 2 MV and Co 60	0.005 to 0.010 (0.13 to 0.25 mm)	0.010 (0.25 mm)
2 to 4 MV	0.010 (0.25 mm)	0.010 (0.25 mm)
4 to 10 MV	0.010 to 0.030 (0.25 to 0.76 mm)	0.010 (0.25 mm)
10 to 25 MV	0.010 to 0.050 (0.25 to 1.3 mm)	0.010 (0.25 mm)

G. Pipe Sizes

TABLE 3.16 Wall thickness of standard steel pipe.

Nominal Size, in.	Outside Diameter		Wall Thickness: Standard Weight Pipe (Schedule 40)		Wall Thickness: Extra Strong Pipe (Schedule 80)		Wall Thickness: Double Extra Strong Pipe (Schedule 160)	
	in.	mm.	in.	mm	in.	mm	in.	mm
1/8	0.405	10.3	0.068	1.7	0.095	2.4		
1/4	0.504	12.8	0.088	2.2	0.119	3.0		
3/8	0.675	17.1	0.091	2.3	0.126	3.2		
1/2	0.840	21.3	0.109	2.8	0.147	3.7	0.294	7.5
3/4	1.105	28.1	0.113	2.9	0.154	3.9	0.308	7.8
1	1.315	33.4	0.133	3.4	0.179	4.5	0.358	9.1
1 1/4	1.660	42.2	0.140	3.6	0.191	4.9	0.382	9.7
1 1/2	1.900	48.3	0.145	3.7	0.200	5.1	0.400	10.2
2	2.375	60.3	0.154	3.9	0.218	5.5	0.436	11.1
2 1/2	2.875	73.0	0.203	5.2	0.276	7.0	0.552	14.0
3	3.500	88.9	0.216	5.5	0.300	7.6	0.600	15.2
3 1/2	4.000	101.6	0.226	5.7	0.318	8.1	0.636	16.2
4	4.500	114.3	0.237	6.0	0.337	8.6	0.674	17.1
4 1/2	5.000	127.0	0.247	6.3	0.355	9.0	0.710	18.0
5	5.563	141.3	0.258	6.6	0.375	9.5	0.750	19.1
6	6.625	168.3	0.280	7.1	0.432	11.0	0.864	21.9
7	7.625	193.7	0.301	7.6	0.500	12.7	0.875	22.2
8	8.625	219.1	0.322	8.2	0.500	12.7	0.875	22.2
9	9.625	244.5	0.342	8.7	0.500	12.7		
10	10.75	273.1	0.365	9.3	0.500	12.7	1.000	25.4
11	11.75	298.5	0.375	9.5	0.500	12.7		
12	12.75	323.9	0.375	9.5	0.500	12.7	1.000	25.4
14	14.00	355.6	0.375	9.5	0.500	12.7		
16	16.00	406.4	0.375	9.5	0.500	12.7		
18	18.00	457.2	0.375	9.5	0.500	12.7		
20	20.00	508.0	0.375	9.5	0.500	12.7		
22	22.00	558.8	0.375	9.5	0.500	12.7		
24	24.00	609.6	0.375	9.5	0.500	12.7		

H. List of Selected ASTM Reference Radiographs

E 155 Aluminum and Magnesium Castings
E 186 Heavy-Walled [2 to 4½-in. (51 to 114-mm)] Steel Castings

E 192 Investment Steel Castings for Aerospace Applications
E 272 High-Strength Copper-Base and Nickel-Copper Alloy Castings
E 280 Heavy-Walled [4½ to 12-in. (114 to 305-mm)] Steel Castings
E 310 Tin Bronze Castings
E 390 Steel Fusion Welds
E 446 Steel Castings up to 2 in. (51 mm) in Thickness
E 505 Aluminum and Magnesium Die Castings
E 689 Ductile Iron Castings
E 802 Gray Iron Castings Up to 4½ in. (114 mm) in Thickness
E 1320 Titanium Castings
E 1648 Aluminum Fusion Welds

References

1. Ewert, U. and Stade, J., "Comparative Analysis of Image Quality from X-Ray Radiography and Gamma Radiography Using Selenium 75 and Iridium 192," *Materials Evaluation,* Vol. 57, No. 2, American Society for Nondestructive Testing, Columbus, OH, February 1999.
2. Bryant, L. E. and McIntire, P., Eds. *Nondestructive Testing Handbook,* 2nd ed., Vol. 3: *Radiography and Radiation Testing,* American Society for Nondestructive Testing, Columbus, OH, 1985.
3. Aman, J. K., Corney, G. M., McBride, D., and Turner, R. E., *Radiography Fundamentals I,* C5L9, Metals Engineering Institute, Metals Park, OH, 1973.
4. Morgan, R. H. and Corrigan, K. E., Eds., *Handbook of Radiology,* Year Book Publishers, Chicago, 1955.
5. Halmshaw, R., *Non-Destructive Testing,* E. Arnold, London, 1987.

ASTM Standards Cited in this Chapter[1]

E 94 Guide for Radiographic Testing
E 747 Practice for Design, Manufacture, and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology
E 1025 Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiology
E 1032 Test Method for Radiographic Examination of Weldments
E 1416 Test Method for Radioscopic Examination of Weldments
E 1647 Practice for Determining Contrast Sensitivity in Radioscopy
E 1742 Practice for Radiographic Examination

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[1] All of these standards are from the *Annual Book of ASTM Standards,* Volume 03.03, *Nondestructive Testing, 2000.*

Notes:

DS68-EB/Feb. 2002

4

Electromagnetic Testing[1]

David Mackintosh[2]

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[1] In this chapter, the term "electromagnetic testing" is used to refer to both conventional eddy current testing and remote field testing (RFT). Table 4.5 is for reference in wire rope testing.

[2] Russell NDE Systems Inc., 4909 75 Ave., Edmonton AB, Canada T6B 2S3.

A. Symbols and Units

TABLE 4.1 Common symbols and units for electromagnetic testing.

Quantity	Symbol	SI Unit and Abbreviation	Other Units Frequently Used in Electromagnetic Testing
Distance or thickness	x	meter (m)	inch, or millimeter (mm)
Diameter	D	meter (m)	inch, or millimeter (mm)
Standard depth of penetration	δ	meter (m)	inch, or millimeter (mm)
Sample thickness or testing depth	τ	meter (m)	inch, or millimeter (mm)
Probe travel speed	v	meter per second (m/s)	inch per second (ips), or millimeter per second (mm/s)
Frequency	f	hertz (Hz)	—
Digital sample rate	r	—	samples per second
Electric potential difference or emf*	E	volt (V)	—
Electric current	I	ampere (A)	—
Capacitance	C	farad (F)	—
Inductance	L	henry (H)	—
Impedance	Z	ohm (Ω)	—
Resistance	R	ohm (Ω)	—
Inductive reactance	X_L	ohm (Ω)	—
Capacitive reactance	X_C	ohm (Ω)	—
Conductivity	σ	siemens per meter (S/m)	percent international annealed copper standard (%IACS)
Resistivity	ρ	ohm · meter ($\Omega \cdot$ m)	microohm · centimeter ($\mu\Omega \cdot$ cm)
Magnetic flux	Φ	weber (W)	—
Magnetic flux density	B	tesla (T)	gauss (G)
Magnetic field strength	H	ampere per meter (A/m)	oersted (Oe)
Magnetic permeability	μ	henry per meter (H/m)	—
Phase or indication angle	θ	radians (rad)	degrees (°)
Phase lag	β	radians (rad)	degrees (°)
Angular frequency	ω	radians per second (rad/s)	—
Fill factor	η	—	[dimensionless]
Amplitude attenuation factor	a	—	[dimensionless]

Notes on Table 4.1:

- Greek letters used are β = beta, δ = delta, η = eta, θ = theta, μ = mu, π = pi, ρ = rho, σ = sigma, τ = tau, Φ = uppercase phi, ω = omega.
- *emf is "electromotive force."

B. Quantities and Conversion Equations for Electromagnetic Testing

The symbol "=" indicates that two quantities are exactly equal by definition; "≈" indicates that a quantity has been rounded to a convenient value.

Fundamental mathematical constants:
$\pi \approx 3.14159$
$e \approx 2.71828$ (base of natural logarithms)

Permeability, μ:
Permeability of vacuum $\mu_0 = 4\pi \times 10^{-7}$ H/m $\approx 1.2566 \times 10^{-6}$ H/m
In a vacuum, relative permeability $\mu_r = 1$ (dimensionless quantity)

Length or distance:
1 in. = 2.54 cm = 0.0254 m (exact)

Conductivity, σ:
International Annealed Copper Standard (IACS):
100%IACS $\approx 5.800 \times 10^5$ S/m

Resistivity, ρ:
$1\ \Omega \cdot \text{m} = 10^8\ \mu\Omega \cdot \text{cm}$

Conductivity, σ, and resistivity, ρ:

$$\sigma = \frac{1}{\rho}; \qquad \rho = \frac{1}{\sigma}$$

where σ is conductivity, S/m
ρ is resistivity, $\Omega \cdot$ m.

$$\rho \approx \frac{1}{(0.0058)\sigma} \approx \frac{172.41}{\sigma},$$

$$\sigma \approx \frac{1}{(0.0058)\rho} \approx \frac{172.41}{\rho},$$

where σ is conductivity, %IACS
ρ is resistivity, $\mu\Omega \cdot \text{cm}$.

Magnetic flux density, B:
$1\ \text{T} = 10^4\ \text{G}$

Magnetic field strength, H:
$1\ \text{A/m} = 4\pi \times 10^{-3}\ \text{Oe} \approx 0.012566\ \text{Oe}$

Angle:
$1\ \text{radian} = 180/\pi\ \text{degrees} \approx 57.3°$

C. Notes on Terminology for Electromagnetic Testing

There is a lack of consensus on terminology among many textbooks on magnetics and electromagnetic testing. This section is intended to help the reader deal with the confusion.

SI and CGS Systems

- SI is the universal abbreviation for the "International System of Units."
- Units of gauss and oersted are associated with the CGS (centimeter-gram-second) system.

Magnetic Fields

- *Magnetic flux density, B,* is also often referred to as *magnetic induction.*
- *Magnetic field strength, H,* is also often referred to as *magnetic field, magnetic field intensity,* or *magnetizing force.*
- In informal usage, and even in some texts, the term *magnetic field* may refer to either B or H.

Magnetic Permeability

- The modern symbol for *permeability* of vacuum is μ_0. The modern symbol for *relative permeability* is μ_r, a dimensionless quantity.

- In informal usage, and even in some texts, the term *permeability* may refer to the *relative permeability,* μ_r.
- In the SI system, the *relative permeability* of vacuum is $\mu_r = 1$. In the CGS system, the *permeability* of vacuum is 1. The *relative permeability* in SI units is numerically equal to the *permeability* in CGS units.

Phase

- The word *phase* has different meanings in different texts, and is often used incorrectly. It is important to be aware of the context and definition used in each text.
- The basic definition of *phase,* paraphrased from ASTM E 1316, Section C, is a time delay expressed in terms of a 360° AC cycle. This definition is especially useful for expressing time delay in send-receive systems and in specifying a phase lag due to skin depth effects.
- *Phase* may also represent an angle of an indication on the impedance plane or other angles which may or may not be equivalent to time delay.

Standard Depth of Penetration

- A *standard depth of penetration* is often referred to in magnetics texts as a *skin depth,* and its formula is derived using *skin depth theory.*

D. Standard Depth of Penetration

$$\delta \approx 1.98\sqrt{\frac{\rho}{f\mu_r}} \approx \frac{26}{\sqrt{f\mu_r\sigma}} \qquad [\delta \text{ in inches}]$$

$$\delta \approx 50\sqrt{\frac{\rho}{f\mu_r}} \approx \frac{661}{\sqrt{f\mu_r\sigma}} \qquad [\delta \text{ in mm}]$$

where ρ = resistivity, $\mu\Omega \cdot$ cm,
σ = conductivity, %IACS,
μ_r = relative permeability (dimensionless) (Note: $\mu_r \approx 1$ for nonferromagnetic materials),

f = frequency, Hz, and
δ = standard depth of penetration in units indicated.

TABLE 4.2 Standard depth of penetration.

Depth	Amplitude Compared to Surface Value	Phase Lag
0 (surface)	$e^0 = 100\%$	0 rad = 0°
δ	$e^{-1} \approx 37\%$	1 rad ≈ 57.3°
2δ	$e^{-2} \approx 14\%$	2 rad ≈ 114.6°
3δ	$e^{-3} \approx 5\%$	3 rad ≈ 171.9°
4δ	$e^{-4} \approx 2\%$	4 rad ≈ 229.2°
$n\delta$	e^{-n}	n rad = $n \cdot 180/\pi°$

The length of one standard depth of penetration, or skin depth, is δ. According to skin depth theory, one depth of penetration is associated with:

- amplitude attenuation to $e^{-1} \approx 37\%$ of initial value, and
- a phase lag of 1 radian ≈ 57.3°.

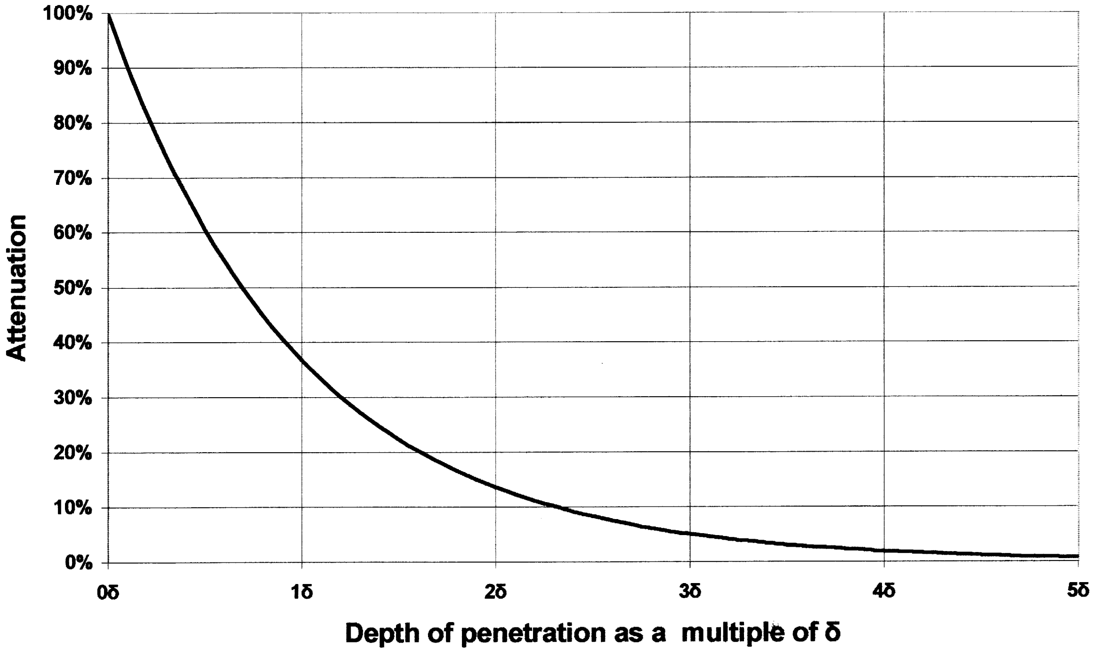

FIG. 4.1 Amplitude attenuation by skin depth theory.

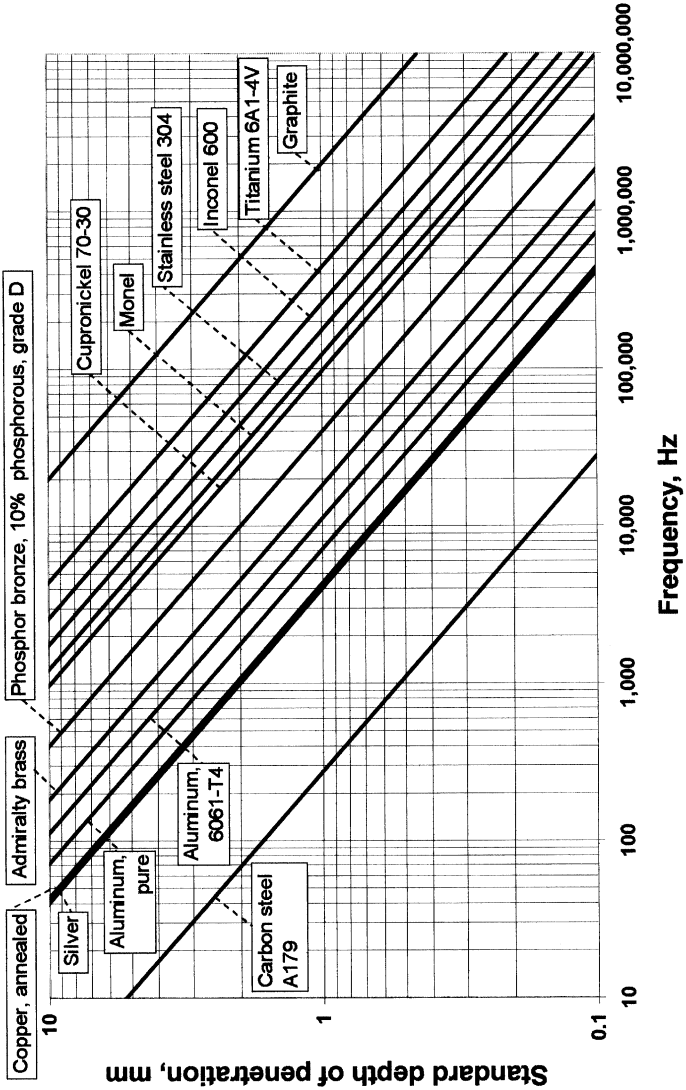

FIG. 4.2 Standard depth of penetration for selected materials.

E. Estimating Operating Frequency

Equations for the optimum operating frequency vary according to textbook, application, and instrument.

In All Equations in this Section,

ρ = resistivity, $\mu\Omega \cdot \text{cm}$

μ_r = relative permeability (dimensionless). Note that $\mu_r \approx 1$ for nonferromagnetic materials.

Tubular Testing (nonferromagnetic):

The equations below set 1.1 standard depths of penetration equal to the wall thickness for nonferromagnetic materials.

f_{90} is the frequency, in Hz, which tends to yield 90° separation between indications from fill-factor variations (including small internal flaws) and indications from small external flaws [1].[3]

$$f_{90} = \frac{3070\rho}{\tau^2} \qquad \text{where } \tau \text{ is wall thickness, mm.}$$

$$f_{90} = \frac{4.8\rho}{\tau^2} \qquad \text{where } \tau \text{ is wall thickness, inches.}$$

Tubular Testing—ASME and RFT:

The equations below set 1.6 standard depths of penetration equal to the wall thickness, and are often used [2] to make a *preliminary estimate* of the frequency required to meet the ASME code for conventional eddy current testing [3]. Use of these equations does not guarantee compliance with the ASME code. These equations are also suitable for remote field testing (RFT).

f_0 is the operating frequency, in Hz.

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[3] Numerals in brackets designate references listed at the end of the chapter.

$$f_0 = \frac{6480\rho}{\tau^2 \mu_r} \qquad \text{where } \tau \text{ is wall thickness, mm.}$$

$$f_0 = \frac{10\rho}{\tau^2 \mu_r} \qquad \text{where } \tau \text{ is wall thickness, inches.}$$

Flat Plate Testing (nonferromagnetic):

The equations below set 0.8 standard depths of penetration equal to the test thickness for nonferromagnetic materials. (Note: The "test thickness" is the required depth of testing in the object, which may be the same as the wall thickness.)

f_0 is the operating frequency, in Hz, which yields 90° separation between "lift-off" and "change in thickness" indications [1].

$$f_o = \frac{1620\rho}{\tau^2} \qquad \text{where } \tau \text{ is test thickness, mm.}$$

$$f_o = \frac{2.5\rho}{\tau^2} \qquad \text{where } \tau \text{ is test thickness, inches.}$$

F. Useful Equations for Electromagnetic Testing

Phase Lag According to Skin Depth Theory:

$$\beta = \frac{x}{\delta} \qquad [\beta \text{ in radians}]$$

$$\beta \approx \frac{x}{\delta} \cdot 57.3 \qquad [\beta \text{ in degrees}]$$

where β = phase lag, expressed in units indicated,
x = depth or thickness, and
δ = standard depth of penetration.
(x and δ must be expressed in the same units.)

Amplitude Attenuation Factor According to Skin Depth Theory:

$$a = e^{-x/\delta}$$

where a = factor of attenuation expressed as a fraction of initial value,
x = depth or thickness, and
δ = standard depth of penetration.
(x and δ must be expressed in the same units).

Angular Frequency:

$$\omega = 2\pi f$$

where ω = angular frequency, radians per second,
f = frequency, Hz.

Fill Factor:

$$\eta = \frac{D_1^2}{D_2^2}$$

where η = fill factor, and
D_1 and D_2 = smaller and larger diameters, respectively, expressed in the same units.

For tubular testing with coil inside tube, D_1 is the coil outside diameter and D_2 is the tube inside diameter.

For testing using an encircling coil, D_1 is the test object outside diameter and D_2 is the coil inside diameter.

Note that some texts use the coil *average* diameter.

Resistance of a Wire:

$$R = \frac{\rho l}{A}$$

where R = resistance of wire, Ω,
ρ = resistivity, Ω · m,
l = length of wire, m,
A = cross-sectional area of wire, m^2.

Ohm's Law:

$$E = IZ$$

where E = emf (electromotive force), V,
I = electric current, A, and
Z = resistance (or impedance for AC circuits), Ω.
(Note: values will be complex for AC circuits.)

Impedance of an Inductor (inductive reactance):

$$X_L = \omega L = 2\pi f L$$

where X_L = magnitude of the inductive reactance, Ω,
ω = angular frequency, rad / s,
f = operating frequency, Hz, and
L = inductance, H.

Impedance of a Capacitor (capacitive reactance):

$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

where X_C = magnitude of the capacitive reactance, Ω,
ω = angular frequency, rad / s,
f = operating frequency, Hz, and
C = capacitance, F.

Total Impedance:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

$$\tan\,\theta = \frac{X_L - X_C}{R}$$

where Z = magnitude of the impedance, Ω,
R = resistance, Ω,
X_L = inductive reactance, Ω,
X_C = capacitive reactance, Ω, and
θ = phase angle of the total impedance.

Note: to calculate the impedance of probes, it is common to set $X_C \approx 0$.

Effective Diameter of Probe Sensing Area:

$$D_{\text{eff}} = D_c + 4\delta$$

where D_{eff} = effective diameter,
D_c = actual diameter of the coil, and
δ = standard depth of penetration, calculated at the operating frequency.

Note: D_{eff}, D_c, and δ must be expressed in the same units.

Magnetic Permeability:

$$\mu = \frac{B}{H}$$

$$\mu = \mu_0 \mu_r$$

where μ = magnetic permeability, H / m,
μ_o = permeability of vacuum ($\mu_o = 4\pi \times 10^{-7}$ H / m),
μ_r = relative permeability (dimensionless),
B = magnetic flux density, T,
H = magnetic field strength, A / m.

Magnetic Flux:

$$\Phi = BA$$

where Φ = total magnetic flux, W,
B = magnetic flux density, T (assumed constant),
A = area of interest, m^2.

Voltage Output of a Coil in an AC Magnetic Field Perpendicular to the Area Encircled by the Coil:

$$V = \omega \Phi N = \omega BAN = 2\pi fBAN$$

where V = magnitude of the voltage induced in the coil, V,
ω = angular frequency, rad / s,
Φ = magnetic flux enclosed by one turn in the coil, W,
N = number of turns in the coil,
B = density of magnetic flux perpendicular to the surface of the coil, assumed constant, T,
A = area encircled by the coil, m^2,
f = frequency, Hz.

Distance between Digital Samples:

$$x = \frac{v}{r}$$

where x = space between samples, in units of distance,
v = probe travel speed, in the same units of distance per second,
r = digital sample rate, in samples per second.

G. Electrical and Electromagnetic Properties of Metals and Alloys

TABLE 4.3 Electrical properties of common metals and alloys. Typical values only, at room temperature. Commercial grade, unless indicated as "pure."

Material	Resistivity, $\mu\Omega \cdot$ cm	Conductivity, %IACS
Aluminum, pure	2.83	60.9
Aluminum, 99.99%	2.66	64.8
Aluminum alloys, cast:		
Allcast, as cast	6.39	27.0
Allcast, sol. h.t. and stress relieved	4.79	36.0
Allcast, sol. h.t. and aged	5.75	30.0
Allcast, stress relieved	5.75	30.0
Alloy 108	5.56	31.0
Alloy A108	4.66	37.0
Alloy 113	5.75	30.0
Alloy C113	6.39	27.0
Alloy 122, perm. mold, as cast	5.07	34.0
Alloy 122-T2, sand cast	4.21	41.0
Alloy 122-T61, sand cast	5.23	33.0
Alloy A132-T551	5.95	29.0
Alloy 142-T61, perm. mold	5.39	32.0
Alloy 142-T21, sand cast	3.92	44.0
Alloy 142-T571, sand cast	5.07	34.0
Alloy 142-T77, sand cast	4.66	37.0
Alloy 195-T4	4.93	35.0
Alloy 195-T62	4.66	37.0
Alloy B195-T4	4.93	35.0
Alloy B195-T6	4.79	36.0
Alloy 214	4.93	35.0
Alloy A214	5.23	33.0
Alloy 218	7.18	24.0
Alloy 220	8.21	21.0
Alloy R317	5.75	30.0
Alloy 319, perm. mold	6.16	28.0
Alloy 319, sand cast	6.39	27.0
Alloy 355-T6 perm. mold	4.42	39.0
Alloy 355-T51 sand cast	4.01	43.0
Alloy 355-T6 sand cast	4.79	36.0
Alloy 355-T61 sand cast	4.66	37.0
Alloy 355-T7 sand cast	4.11	41.9
Alloy 356-T51 sand cast	4.01	43.0
Alloy 356-T6, sand cast	4.42	39.0
Alloy 360	4.66	37.0
Alloy 380	6.39	27.0
Alloy 750	3.83	45.0

Continues on next page

TABLE 4.3 *continued.*

Material	Resistivity, $\mu\Omega \cdot$ cm	Conductivity, %IACS
Aluminum alloys, wrought:		
Alloy 1100	2.90	59.5
Alloy 2011-T3	4.76	36.2
Alloy 2014-F and -0	3.47	49.7
Alloy 2014-T3 and -T4	5.12	33.7
Alloy 2014-T6	4.44	38.8
Alloy 2017-F	3.49	49.4
Alloy 2017-0	3.83	45.0
Alloy 2017-T4	5.75	30.0
Alloy 2024-F	3.62	47.6
Alloy 2024-0	3.45	50.0
Alloy 2024-T3	5.33	32.3
Alloy 2024-T36	5.88	29.3
Alloy 2024-T4	5.77	29.9
Alloy 2024-T6	4.31	40.0
Alloy 2127-T4	4.08	42.3
Alloy 2218-T61	4.61	37.4
Alloy 2618	4.29	40.0
Alloy 3003-0	3.65	47.2
Alloy 3003-H12 and -H14	3.86	44.7
Alloy 3003-H18	4.31	40.0
Alloy 3003-H24 and -H28	4.04	42.7
Alloy 3004	4.16	41.4
Alloy 3005-0	3.44	50.1
Alloy 3032-0	4.31	40.0
Alloy 3032-T6	4.93	35.0
Alloy 4032-T6	4.82	35.8
Alloy 4043-F	3.24	53.2
Alloy 5005	3.28	52.6
Alloy 5050	3.52	49.0
Alloy 5051-0	3.14	54.9
Alloy 5051-T4 and -T6	3.83	45.0
Alloy 5052	4.84	35.6
Alloy 5053-0	3.83	45.0
Alloy 5053-T4 and -T6	4.31	40.0
Alloy 5056-0	5.95	29.0
Alloy 5056-H38	6.39	27.0
Alloy 5154	5.45	31.6
Alloy 5357	3.86	44.7
Alloy 6053	3.95	43.6
Alloy 6061-F and -0	3.80	45.4
Alloy 6061-T4	4.42	39.0
Alloy 6061-T6 and -T9	4.07	42.4
Alloy 6062-F	3.52	49.0
Alloy 6062-T4	3.94	43.8
Alloy 6062-T6	3.66	47.1
Alloy 6151-0	3.18	54.2
Alloy 6151-T4	4.07	42.4

Continues on next page

TABLE 4.3 *continued.*

Material	Resistivity, $\mu\Omega \cdot$ cm	Conductivity, %IACS
Alloy 6151-T6	3.88	44.4
Alloy 6951-F	3.25	53.1
Alloy 6951-0	3.07	56.2
Alloy 7072	2.87	60.1
Alloy 7075-F	3.74	46.1
Alloy 7075-T6	5.39	32.0
Alloy 7075-W	5.39	32.0
Alloy 7178-F and -0	3.77	45.7
Alloy 7178-W and -T6	5.81	29.7
Antimony	39.2	4.40
Babbit, lead base	28.7	6.01
Beryllium	4.00	43.1
Beryllium copper, Condition A	10.1	17.1
Beryllium copper, Condition At	8.21	21.0
Brasses:		
Admiralty brass	7.18	24.0
Aluminum brass, annealed	7.50	23.0
Cartridge brass, annealed	6.16	28.0
Commercial bronze, annealed	3.92	44.0
Leaded commercial bronze	4.11	42.0
Gilding metal, annealed	3.08	56.0
Low brass, annealed	5.39	32.0
Leaded low brass, annealed	6.63	26.0
Muntz metal, annealed	6.16	28.0
Naval brass, annealed	6.63	26.0
Leaded naval brass, annealed	6.63	26.0
Red brass, annealed	4.66	37.0
Leaded semi-red brass	9.58	18.0
Yellow brass, annealed	6.39	27.0
High-strength yellow brass	14.4	12.0
Leaded yellow brass	6.90	25.0
Bronzes:		
Aluminum bronze	12.3	14.0
Aluminum bronze, 5% aluminum, annealed	9.85	17.5
Aluminum bronze, 10% aluminum, annealed	13.7	12.6
Leaded tin bronze	12.3	14.0
Leaded tin bearing bronze	15.7	11.0
Manganese bronze, annealed	7.18	24.0
Phosphor bronze, 1.25% phosphorous, Grade E	3.59	48.0
Phosphor bronze, 5% phosphorous, Grade A	9.58	18.0

Continues on next page

TABLE 4.3 *continued.*

Material	Resistivity, $\mu\Omega \cdot$ cm	Conductivity, %IACS
Phosphor bronze, 8% phosphorous, Grade C	13.3	13.0
Phosphor bronze, 10% phosphorous, Grade D	15.7	11.0
Silicon bronze, type A, annealed	24.6	7.01
Silicon bronze, type B, annealed	14.4	12.0
Cadmium	6.84	25.2
Calcium	3.54	48.7
Chromium	19.6	8.80
Columbium	13.1	13.2
Copper, deoxidized, annealed	2.03	84.9
Copper, electrolytic tough pitch, annealed	1.71	101
Copper, annealed (standard)	1.72	100
Cupronickel 90-10	17.7	9.74
Cupronickel 70-30	38.3	4.50
Cupronickel 55-45 (constantan)	49.0	3.52
Gold	2.35	73.4
Graphite	783.7	0.220
Hastelloy A	123.2	1.40
Hastelloy B and C	132.6	1.30
Hastelloy D	114.9	1.50
Hastelloy X	114.9	1.50
Inconel	98.0	1.76
Inconel 600	101.4	1.70
Iridium	5.29	32.6
Iridium-platinum alloys	19.0	9.07
Iron	9.58	18.0
Ingot iron, 99.9% Fe	11.1	15.5
White cast iron	15.5	11.1
Lead	20.5	8.41
Lead, 1% antimony, quenched and aged	21.9	7.87
Lead, Corrodine	20.8	8.29
Lead, hard, quenched and aged	22.4	7.70
Lithium	8.54	20.2
Magnesium, pure	4.47	38.6
Magnesium alloys:		
Alloy AZ31	10.0	17.2
Alloy AZ51	13.5	12.8
Alloy AZ61	14.0	12.3
Alloy AZ80	11.8	14.6
Alloy T454	13.8	12.5
Molybdenum	5.23	33.0

Continues on next page

TABLE 4.3 *continued.*

Material	Resistivity, $\mu\Omega \cdot$ cm	Conductivity, %IACS
Monel	48.2	3.58
Nickel, pure (electrolytic)	6.84	25.2
Nickel “A”	9.58	18.0
Nickel-silver (copper alloy), 18% Ni	28.7	6.01
Osmium	9.47	18.2
Palladium	10.8	16.0
Platinum	10.6	16.3
Platinum, commercial	14.9	11.6
Platinum-ruthenium, contact grade	43.1	4.00
Platinum-ruthenium, jewelry grade	31.4	5.44
Rhodium	4.49	38.4
Ruthenium	7.60	22.7
Selenium	12.0	14.4
Silver, pure	1.59	108
Solders:		
Tin-lead, 5-95	19.6	8.80
Tin-lead, 20-80	17.6	9.80
Tin-lead, 50-50	15.7	11.0
Tin-antimony	14.5	11.9
Tin-silver	10.4	16.6
Steel:		
A106	16.2	10.6
High alloy	59.5	2.90
Stainless, type 304	69.0	2.50
Stainless, type 316	75.0	2.30
Stainless, type 347	71.8	2.40
Tantalum	12.4	13.9
Tin, pure	11.5	15.0
Tin foil	41.1	4.19
Titanium	55.6	3.10
Titanium, commercial	78.4	2.20
Titanium, 6A1-4V alloy	172.4	1.00
Tungsten	5.49	31.4
Uranium	28.7	6.01
Vanadium	26.1	6.61
Waspaloy	123.2	1.40
Zinc	5.95	29.0
Zinc, commercial rolled	6.16	28.0
Zinc, die cast	6.39	27.0
Zircaloy-2	71.8	2.40
Zirconium	50.7	3.40

Table 4.3 adapted from [4] with permission of Eddy Current Technology Incorporated, 201A Horace Avenue, Virginia Beach, VA 23462, telephone (757)490-1814, Fax (757)490-2778, e-mail montyoc@pilot.infini.net.

TABLE 4.4 Electromagnetic properties of selected carbon steels. Typical values only, at room temperature, for carbon steels used in tubing.

Material	Resistivity, ρ, $\mu\Omega \cdot$ cm	Conductivity σ, %IACS	Relative Permeability, μ_r	Product of Conductivity and Relative Permeability, $\sigma \cdot \mu_r$ %IACS
A106	16.2	10.6	141	1551
A178	13.6	12.7	166	2158
A179	17.7	9.74	162	1620
A214	14.9	11.6	132	1584
A519 Gr 1020	14.9	11.6	109	1308

Source: Russell NDE Systems Inc., 4909 75 Ave., Edmonton, Canada T6B 2S3, tel. 780-468-6800, www.russelltech.com.

Notes on Table 4.4:

- With carbon steels, values may vary widely between samples.
- Permeability values were measured using magnetic field levels typically generated inside tube walls by a remote field probe (10^{-3} to 10^{-5} T).
- The product of conductivity and relative permeability, $\sigma \cdot \mu_r$, allows a comparison of different carbon steels. The product $\sigma \cdot \mu_r$ also allows a comparison with the conductivity values for nonferromagnetic materials, as used to calculate standard depth of penetration.

H. Wire Rope

TABLE 4.5 Approximate metallic areas and masses of one-inch rope of various constructions.

Construction	Fiber Core Area, sq. in.	Mass, lb/ft	Mass, kg/m	IWRC Area, sq. in.	Mass, lb/ft	Mass, kg/m
6×6	0.320			0.386		
6×7	0.384	1.50	2.23	0.451	1.65	2.46
6×19 Seale	0.404	1.68	2.50	0.470	1.85	2.75
6×19 Warrington	0.416	1.68	2.50	0.482	1.85	2.75
6×21 Filler Wire	0.412	1.68	2.50	0.478	1.85	2.75
6×21 Seale	0.411	1.68	2.50	0.477	1.85	2.75
6×25 Filler Wire	0.417	1.68	2.50	0.483	1.85	2.75
6×26 Warrington Seale	0.409	1.68	2.50	0.476	1.85	2.75
6×31 Warrington Seale	0.414	1.68	2.50	0.481	1.85	2.75
6×36 Warrington Seale	0.419	1.68	2.50	0.485	1.85	2.75
6×41 Warrington Seale	0.424	1.68	2.50	0.490	1.85	2.75
6×25 Flattened Strand	0.469	1.80	2.68	0.529	1.89	2.83
6×27 Flattened Strand	0.455	1.80	2.68	0.515	1.89	2.83
6×31 Flattened Strand	0.480	1.80	2.68	0.540	1.89	2.83
8×19 Seale	0.359	1.57	2.34	0.472	1.88	2.80
8×25 Filler Wire	0.368	1.57	2.34	0.499	1.88	2.80
18×7 Rot. Resist.	0.422	1.73	2.57			
19×7 Rot. Resist.				0.453	1.82	2.71

Source: reference [5]

Note on Table 4.5: To obtain area and mass for diameters other than 1 in., multiply the area and mass given in this table by the square of the nominal rope diameter in inches.

References

1. Cecco, V. S., Van Drunen, G., and Sharp F. L., *AECL-7523 Eddy Current Manual, Volume I: Test Method,* Atomic Energy of Canada Ltd., 1983.
2. Davis, J. M., and King, M., *Mathematical Formulas and References for Nondestructive Testing: Eddy Current,* the Art Room Corporation, 1994.
3. American Society of Mechanical Engineers (ASME), *1998 ASME Boiler and Pressure Vessel Code, Section V: Nondestructive Examination, Article 8: Eddy Current Examination of Tubular Products,* ASME, 1998.
4. Eddy Current Technology Ltd., *Electrical conductivity of materials—Report ECT R8418-R1.*
5. Wire Rope Technical Board, *Wire Rope Users Manual,* 3rd ed., 1993.

Sources

IEEE-ASTM-SI-10 IEEE / ASTM SI-10 Standard for Use of the International System of Units (SI): The Modern Metric System.

Griffiths, David J., *Introduction to Electrodynamics,* 3rd ed., Prentice Hall, 1998.

Harvey, Dane E., *Eddy Current Testing: Theory and Practice,* American Society for Nondestructive Testing, 1995.

Notes:

5

Penetrant Testing

Sam Robinson[1]

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[1] Sherwin Inc.—East, 1615 Distribution Drive, Burlington, KY 41005.

TABLE 5.1 Penetrant material classification.

Type 1	Fluorescent Dye
Type 2	Visible Dye
Method A	Water Washable
Method B	Post Emulsifiable, Lipophilic
Method C	Solvent Removable
Method D	Post Emulsifiable, Hydrophilic
Sensitivity Level ½	Ultra Low
Sensitivity Level 1	Low
Sensitivity Level 2	Medium
Sensitivity Level 3	High
Sensitivity Level 4	Ultra High

Note: Sensitivity level ½ applies to Type 1, Method A penetrants only. There is no sensitivity level classification for Type 2 penetrant systems.

Developers shall be of the following forms:

Form a	Dry Powder
Form b	Water Soluble
Form c	Water Suspendible
Form d	Nonaqueous Type I Fluorescent (solvent based)
Form e	Nonaqueous Type II Visible Dye (solvent based)
Form f	Special Application

Solvent Removers shall be of the following classes:

Class 1	Halogenated
Class 2	Non-Halogenated

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TABLE 5.2 Acceptance tests.

The acceptance tests that shall be performed on each batch are specified in the designated paragraphs of AMS 2644.[A]

Penetrant Tests:	
Flash Point	3.3.3
Viscosity	3.3.4
Fluorescent Brightness	3.3.8.3.2
Water Tolerance (Method A only)	3.3.8.5
Removability	3.3.8.6
Emulsifier Tests:	
Flash Point	3.3.3
Viscosity	3.3.4
Water Content (Method D only)	3.3.9.6
Developer Tests:	
Developer Fluorescence	3.3.10.2
Developer Removability	3.3.10.4
Redispersibility (Forms c, d and e only)	3.3.10.5
Remover Tests:	
Fluorescence (Type 1 use only)	3.3.11

[A] AMS specifications cited in this chapter are referenced at the end of the chapter.

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TABLE 5.3 Brightness requirements.

The fluorescent brightness of Type 1 penetrants shall not be less than the following percentages of brightness of the reference penetrant FP-4PE[A] when tested in accordance with ASTM E 1135.[B]

Level ½	50 Percent
Level 1	65 Percent
Level 2	80 Percent
Level 3	90 Percent
Level 4	95 Percent

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[A] Designations of reference materials are given in Table 5.7.

[B] ASTM Standards cited in this chapter are referenced at the end of the chapter.

TABLE 5.4 Thermal stability requirements.

The thermal stability of the fluorescence of Type 1 penetrants shall be tested in accordance with paragraph 4.4.8 in AMS 2644. The minimum acceptable values are as follows:

Level ½	60 Percent
Level 1	60 Percent
Level 2	60 Percent
Level 3	80 Percent
Level 4	80 Percent

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TABLE 5.5 Ultraviolet stability requirements.

The ultraviolet stability of the fluorescence of Type 1 penetrants shall be tested in accordance with paragraph 4.4.7 in AMS 2644. The minimum acceptable values are as follows:

Level ½	50 Percent
Level 1	50 Percent
Level 2	50 Percent
Level 3	70 Percent
Level 4	70 Percent

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TABLE 5.6 Sensitivity and removability matrix.

Candidate Materials System	Candidate Materials Developer	Reference Materials System	Reference Materials Developer
Type 1, Method A, Level ½	D-a	FP-1/2	D-a
Type 1, Method A, Level 1	D-a	FP-1W	D-a
Type 1, Method B, Level 1	D-a	FP-1PE/FE-B	D-a
Type 1, Method C, Level 1	D-a	FP-1PE/R-1	D-a
Type 1, Method D, Level 1	D-a	FP-1PE/FE-D	D-a
Type 1, Method A, Level 2	D-a	FP-2W	D-a
Type 1, Method B, Level 2	D-a	FP-2PE/FE-B	D-a
Type 1, Method C, Level 2	D-a	FP-2PE/R-1	D-a
Type 1, Method D, Level 2	D-a	FP-2PE/FE-D	D-a
Type 1, Method A, Level 3	D-a	FP-3W	D-a
Type 1, Method B, Level 3	D-a	FP-3PE/FE-8	D-a
Type 1, Method C, Level 3	D-a	FP-3PE/R-1	D-a
Type 1, Method D, Level 3	D-a	FP-3PE/FE-D	D-a
Type 1, Method A, Level 4	D-a	FP-4W	D-a
Type 1, Method B, Level 4	D-a	FP-4PE/FE-B	D-a
Type 1, Method C, Level 4	D-a	FP-4PE/R-1	D-a
Type 1, Method D, Level 4	D-a	FP-4PE/FE-D	D-a
Type 2, Method A	D-e		D-e
Type 2, Method B	D-e		D-e
Type 2, Method C	D-e		D-e
FP-4PE/Class 1	D-a	FP-4PE/R-1	D-a
FP-4PE/Class 2	D-a	FP-4PE/R-2	D-a
FP-4PE/FE-B	Form a	FP-4PE/FE-B	D-a
FP-4PE/FE-B	Form b	FP-4PE/FE-B	D-b
FP-4PE/FE-B	Form c	FP-4PE/FE-B	D-c
FP-4PE/FE-B	Form d	FP-4PE/FE-B	D-d
VPPENE-B	Form a	VPPENE-B	D-e

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TABLE 5.7 Reference material designations.

Reference Material	Designations Method A	 Method B, C & D
Penetrant, Type I, Level ½	FP-1/2	N/A
Penetrant, Type I, Level 1	FP-1W	FP-1PE
Penetrant, Type I, Level 2	FP-2W	FP-2PE
Penetrant, Type I, Level 3	FP-3W	FP-3PE
Penetrant, Type I, Level 4	FP-4W	FP-4PE
Penetrant, Type II	VPW	VPPE
Emulsifier, Type I, Method B	FE-B	FE-B
Emulsifier, Type I, Method D	FE-D	FE-D
Emulsifier, Type II, Method B	VE-B	VE-B
Remover, Class (1)	R-1	R-1
Remover, Class (2)	R-2	R-2
Developer, Form a	D-a	D-a
Developer, Form b	D-b	D-b
Developer, Form c	D-c	D-c
Developer, Form d	D-d	D-d
Developer, Form e	D-e	D-e

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TABLE 5.8A Type I system test parameters.

Process Parameters	Methods A	Methods B	Methods C	Methods D
Prewash	2	2	2	1
Emulsification	2	2 min	2	1,3
Wash	5	4	2	1
Solvent Wipe	2	2	4	2
Dry	1	1	6	1
Developer	7	7	7	7

Legend:
1. Same as reference process.
2. Not applicable.
3. Concentration recommended by manufacturer.
4. As required
5. In accordance with AMS 2644, paragraph 4.4.11.2.
6. 5 minutes at room temperature.
7. All forms (types) for 5 minutes.

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TABLE 5.8B Type 2 system dwell times.

Method	Penetrant, minutes	Emulsifier, minutes	Developer, minutes
A	5	N/A	5
B	5	30	5
C	5	N/A	5

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TABLE 5.9 Schedule of in-use penetrant materials testing (ASTM E 1417).

	Frequency
In-Use Penetrants	
Fluorescent Brightness	quarterly
Water Content (Method A Only)	monthly
*Removability (Method A Only)	monthly
*Sensitivity	weekly
Viscosity	optional
Water Tolerance	optional
*Separation	daily
In-Use Emulsifiers	
*Removability (Method B & D)	monthly
Water Content (Method B)	monthly

*Removability, Sensitivity and Separation are often tested locally by the user.

TABLE 5.10 Tests and test frequency (ASTM E 1417).

Tests	Frequency	Paragraph
System Performance	Daily	7.8.3
Penetrant Contamination	Daily	7.8.2.1
Developer Contamination (Aqueous: Soluble and Suspendable)	Daily	7.8.2.5
Developer Concentration (Aqueous: Soluble and Suspendable)	Weekly	7.8.2.6
Developer Condition (Dry)	Daily	7.8.2.4
Water Wash Pressure[A]	Each shift	7.8.5.4
Water Wash Temperature[A]	Each shift	7.8.5.4
Black Light Intensity	Daily	7.8.5.1
Inspection Area Cleanliness[A]	Daily	7.8.5.3
Water-Based Penetrant Water Concentration	Weekly	7.8.2.2
Non-Water-Based Penetrant (Method A) Water Content	Monthly	7.8.2.2
Emulsifier Concentration (Hydrophilic)	Weekly	7.8.2.7
Penetrant Sensitivity[B]	Weekly	7.8.4.3
Fluorescent Brightness (Test Method E 1135)[B]	Quarterly	7.8.4.1
Penetrant Removability[B]	Monthly	7.8.4.2
Emulsifier Removability[B]	Monthly	7.8.4.4
Emulsifer Water Content (lipophilic)	Monthly	7.8.2.3
Drying Oven Calibration[C]	Quarterly	7.8.5.5
Light Meter Calibration[C]	Semiannually	7.8.5.2

[A] Need not be recorded.

[B] These checks can be combined and performed during the system performance check in accordance with 7.8.4.

[C] The maximum time between verifications may be reduced or extended when substantiated by actual technical/reliability data.

TABLE 5.11 Hydrophilic emulsifier use concentration.

For immersion application, the concentration of emulsifier shall be no higher than the manufacturer's qualified (approved) concentration as specified in QPL 25135 or QPL-AMS-2644.

NOTE:
To help assure that the concentration of the emulsifier does not exceed the manufacturer's qualified concentration, which could negatively affect the system performance, the initial penetrant system should be set up in the shop with the following nominal concentrations.

	Nominal Tank Concentration
For 30% maximum use products:	27%
For 20% maximum use products:	17%
For 10% maximum use products:	7%

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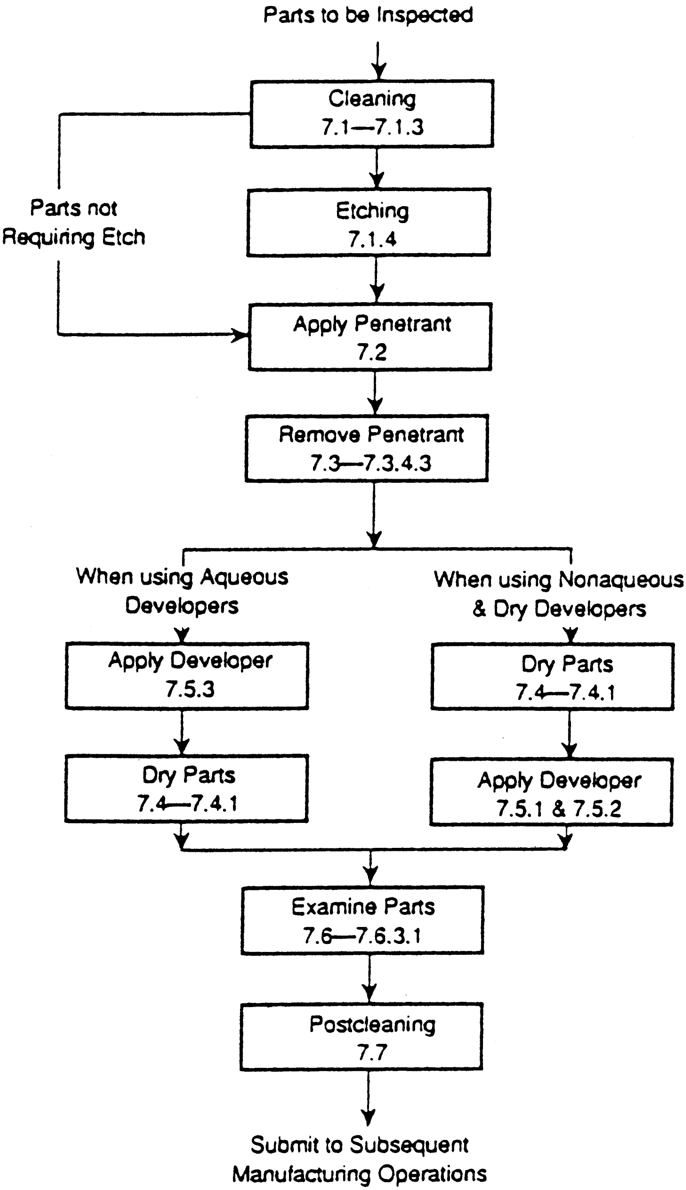
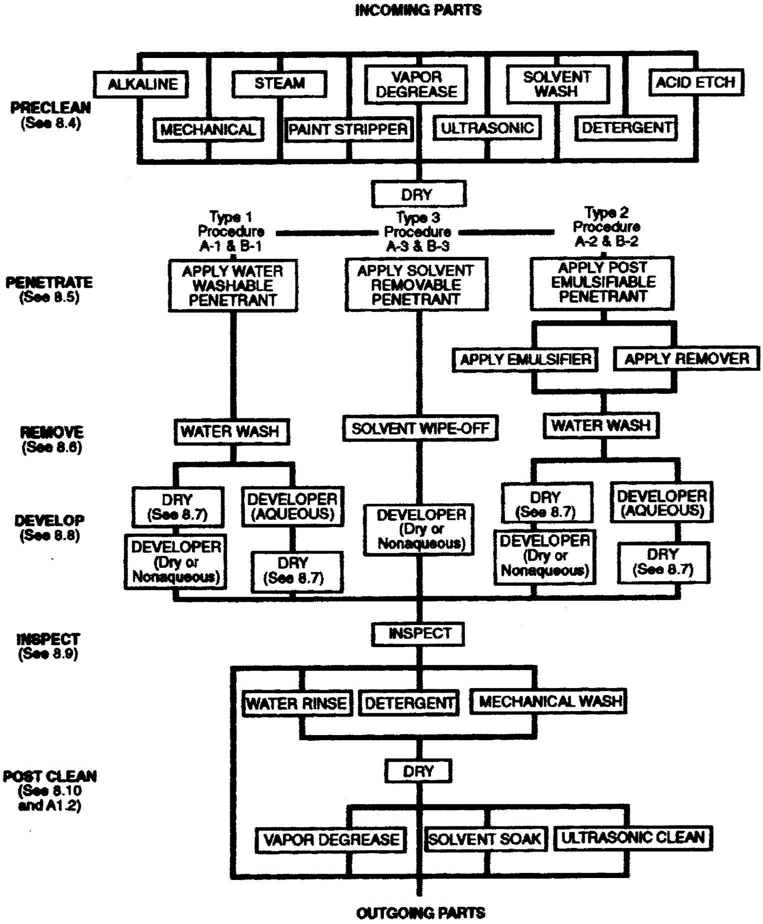


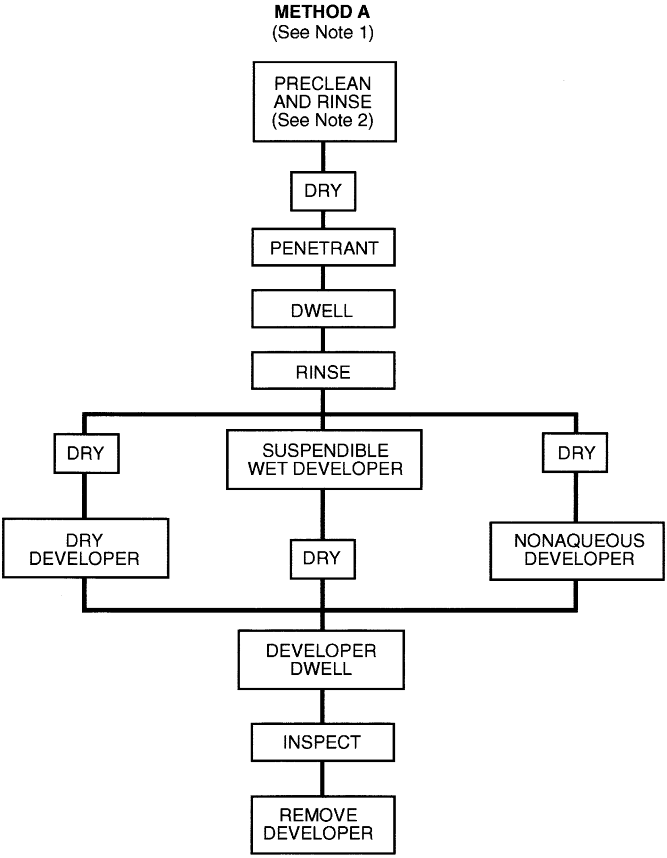
Note: The numbers in this figure refer to paragraphs in ASTM E 1417.

FIG. 5.1 Process flow chart (ASTM E 1417).



Note: The numbers in this figure refer to paragraphs in ASTM E 165.

FIG. 5.2 Fluorescent and visible penetrant inspection general processing procedures flowsheet (ASTM E 165).



NOTE 1. Method A should not be used on major engine rotating components unless otherwise approved by the hardware or component manufacturer.

NOTE 2. Etch may be required to remove smeared metal. Consult part or material specification.

FIG. 5.3 Flow chart for the water washable penetrant inspection process (Method A).

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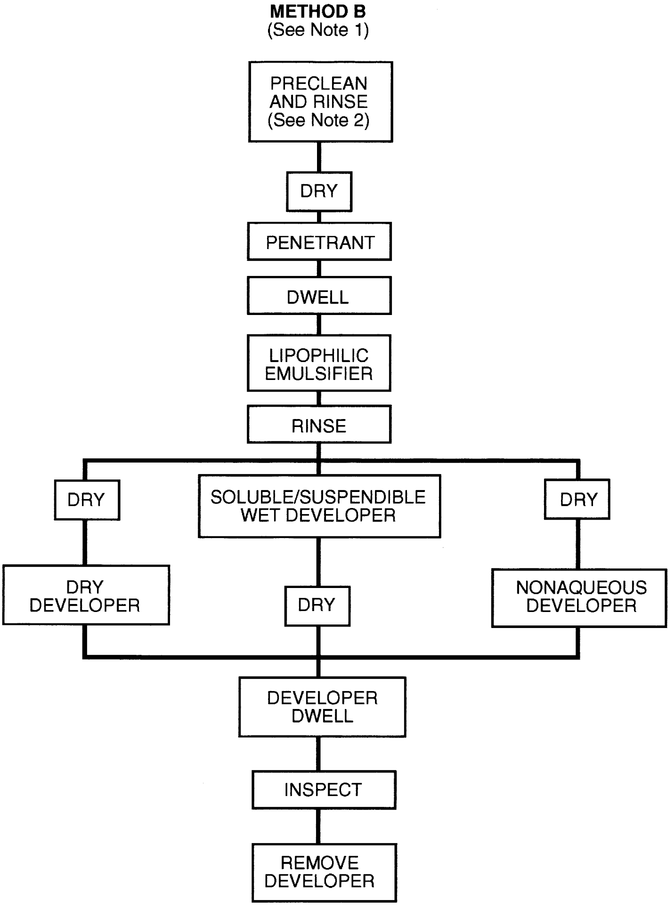

NOTE 1. Method B is not applicable to engine parts.

NOTE 2. Etch may be required to remove smeared metal. Consult part or material specification.

FIG. 5.4 Flow chart for the post emulsifiable (lipophilic) penetrant inspection process (Method B).

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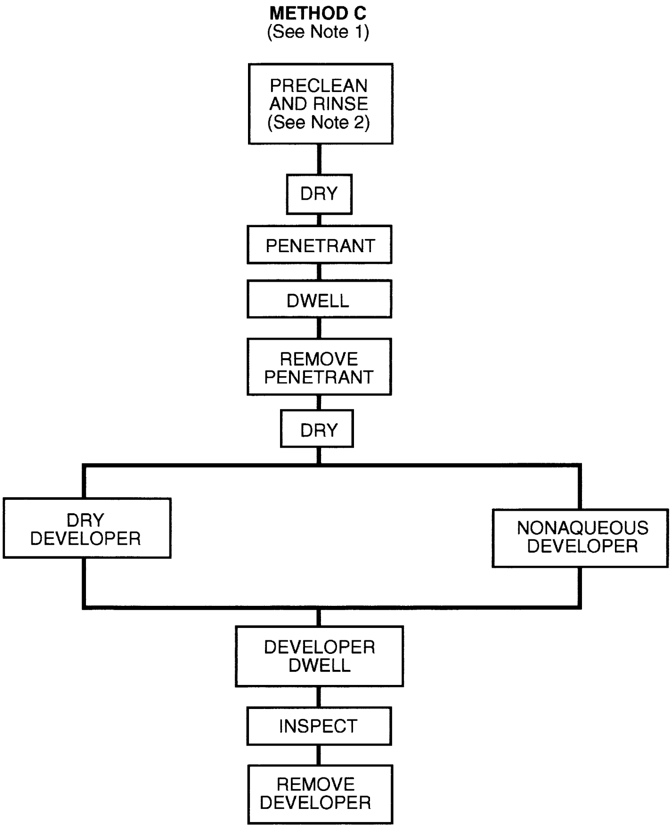

NOTE 1. Method C is for localized areas only.
NOTE 2. Etch may be required to remove smeared metal. Consult part or material specification.

FIG. 5.5 Flow chart for the solvent removable penetrant inspection process (Method C).

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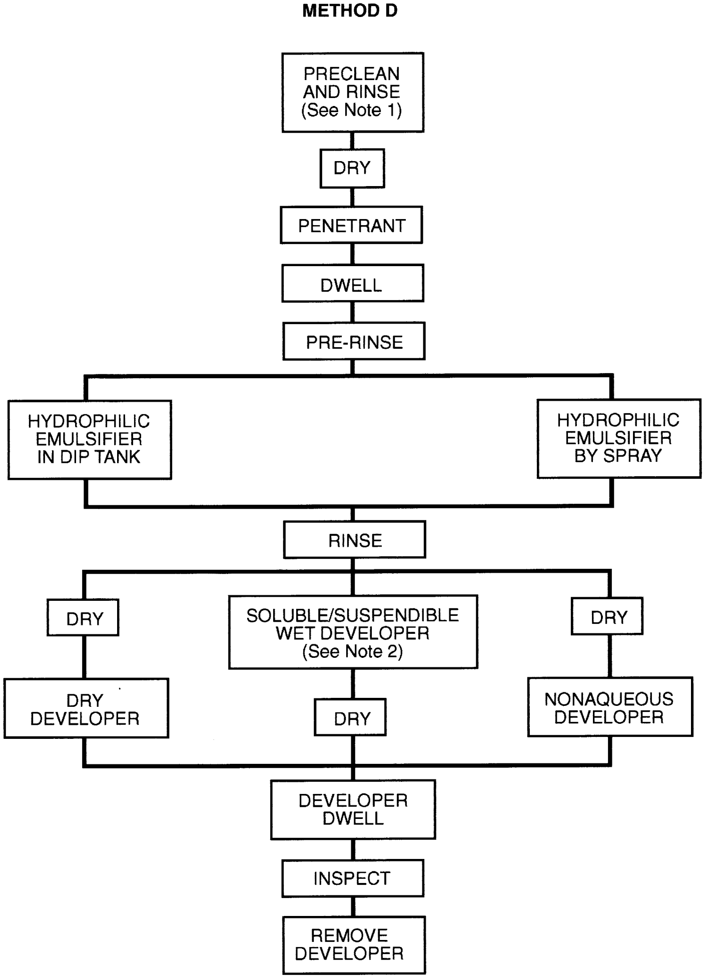

NOTE 1. Etch may be required to remove smeared metal. Consult part or material specification.
NOTE 2. Soluble wet developer is not permissible for use on engine parts.

FIG. 5.6 Flow chart for the post emulsifiable (hydrophilic) penetrant inspection process (Method D).

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TABLE 5.12 Cleaning methods.

	Type	pH	Soils to be Cleaned
Detergent Cleaners	Water Soluble Compounds with Surfactants	Akaline Neutral Acidic	Grease, Oily Films, Cutting Fluids, Drawing Compounds
Solvent Cleaners	Solvent	Neutral	Grease, Oily Films, Waxes, Sealants, Paints, Organic Matter
Vapor Degreasing	Solvent	Neutral	Oil or Grease-Type Soils
Alkaline	Water Solutions	Alkaline	Rust, Descaling, Grease, Oily Films, Cutting Fluids
Steam	Water/Alkaline Detergent	Alkaline	Inorganic Soils, Grease, Oily Films, Cutting Fluids, Waxes
Ultrasonic	Solvent OR Detergent	Neutral Neutral	Grease, Oily Films Rust, Dirt, Salts, Corrosion Products
Mechanical	Glass Beads, Sand, Aluminum Oxide, Plastic Pellets, Metallic Shot	Neutral	Carbon, Rust, Scale, Foundry Sands
Acid Etching	Pickling Solutions	Acidic	Descaling, Oxide Scale, Smeared Metal

TABLE 5.13 Development times (ASTM E 1417).

Developer Type	Minimum Development Time	Maximum Development Time
No Developer	10 min	2 h
Dry Developer	10 min	4 h
Nonaqueous Developer	10 min	1 h
Aqueous Developer	10 min	2 h

TABLE 5.14 Recommended minimum dwell times (ASTM E 165).

			Dwell Times[A] (minutes)	
Material	Form	Type of Discontinuity	Penetrant[B]	Developer[C]
Aluminum, magnesium, steel, brass and bronze, titanium and high-temperature alloys	castings and welds	cold shuts, porosity, lack of fusion, cracks (all forms)	5	10
	wrought materials—extrusions, forgings, plate	laps, cracks (all forms)	10	10
Carbide-tipped tools		lack of fusion, porosity, cracks	5	10
Plastic	all forms	cracks	5	10
Glass	all forms	cracks	5	10
Ceramic	all forms	cracks, porosity	5	10

[A] For temperature range from 50 to 100°F (10 to 38°C) for fluorescent penetrants and 50 to 125°F (10 to 52°C) for visible penetrant.

[B] Maximum penetrant dwell time in accordance with 8.5.2.

[C] Development time begins as soon as wet developer coating has dried on surface of parts (recommended minimum). Maximum development time in accordance with 8.8.6.

TABLE 5.15 Defect standard crack size.

It is permissible to use a defect(s) standard which contains five individual cracks with each of the five cracks appearing as a starburst radiating outward from a localized center. The cracks on this panel shall range in size as follows.

Note: Crack identified below as “A” may appear as a pinpoint instead of a starburst.

Cracks	Crack Size	
A	0.015 to 0.032 in.	(0.38 to 0.79 mm)
B	0.046 to 0.062 in.	(1.17 to 1.57 mm)
C	0.075 to 0.093 in.	(1.91 to 2.36 mm)
D	0.125 to 0.171 in.	(3.18 to 4.34 mm)
E	0.180 to 0.250 in.	(4.57 to 6.35 mm)

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TABLE 5.16 Comparison of light source brightness measurements.

Source	Radiometric Measurements, mW/cm^2	Photometric Measurements, cd/m^2
Candle flame	1×10^4	1.03×10^4
Sun	4.5×10^6	1.5×10^9
Tungsten lamp		
miniature	6×10^4	2.1×10^6
standard	1.3×10^5	8.6×10^6
standard	2.6×10^3	1.7×10^5
photo	2.5×10^5	3.1×10^7
Neon	8×10^{-2}	1.6×10^1
Fluorescent	3×10^1	6.9×10^3
Xenon flash	1.2×10^7	3.4×10^9

NOTE: In the comparison of photometric measurements with radiometric values, note that there is no constant factor that relates the two. Radiometric measurements include the response to power at all radiant wavelengths, while photometric measurements include only the power in the visible wavelengths. For example, the radiometric measurements show that the sun produces approximately 4500 times more mW/cm^2 than a candle flame. However, the photometric data show that the sun produces a sensation of brightness almost 150,000 times more than the candle when the human eye is the sensor. This means that sunlight has a larger percentage of energy in the visible wavelengths than the candle.

(Courtesy of Texas Instruments Inc.)

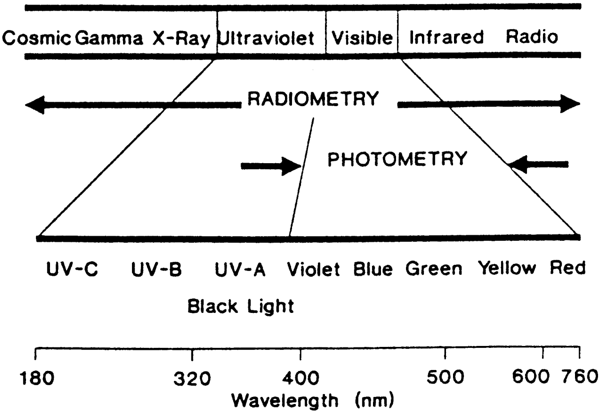

FIG. 5.7 The electromagnetic radiation spectrum [1].

From *Materials Evaluation*, Vol. 41, No. 3. Reprinted with permission of the American Society for Nondestructive Testing. Note: In the three divisions of the ultraviolet spectrum, note that black light is long-wave UV-A and that it is in close proximity to visible light and infrared, which should not be included in black light measurement [2].

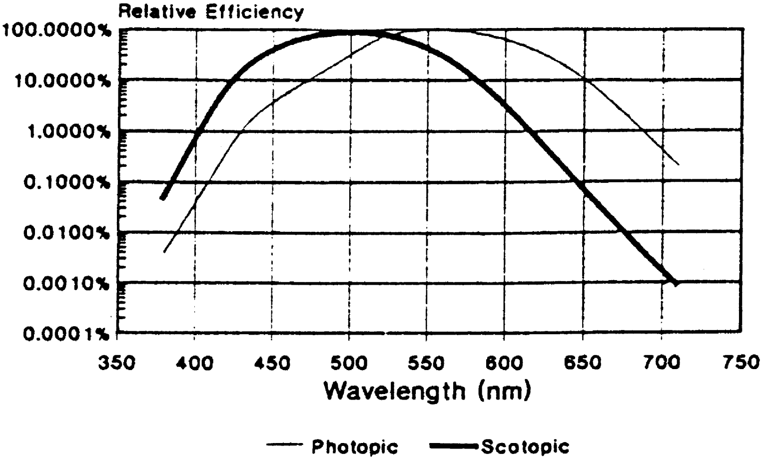

FIG. 5.8 Spectral luminous efficiency of the human eye, photopic and scotopic [1].

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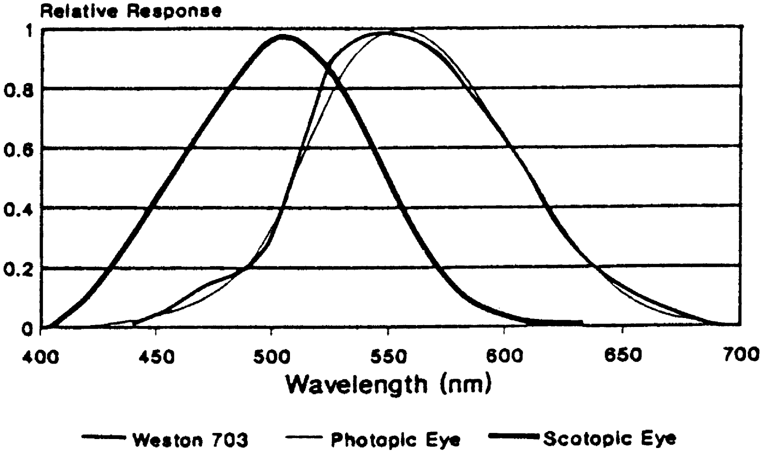

FIG. 5.9 Typical photographic light meter and photopic and scotopic eye responses [1].
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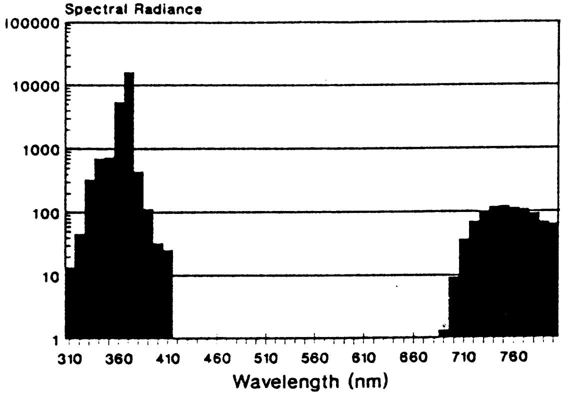

FIG. 5.10 Spectral radiance of PAR 38 bulb with Kopp No. 41 filter [1].
From *Materials Evaluation*, Vol. 41, No. 3. Reprinted with permission of the American Society for Nondestructive Testing.

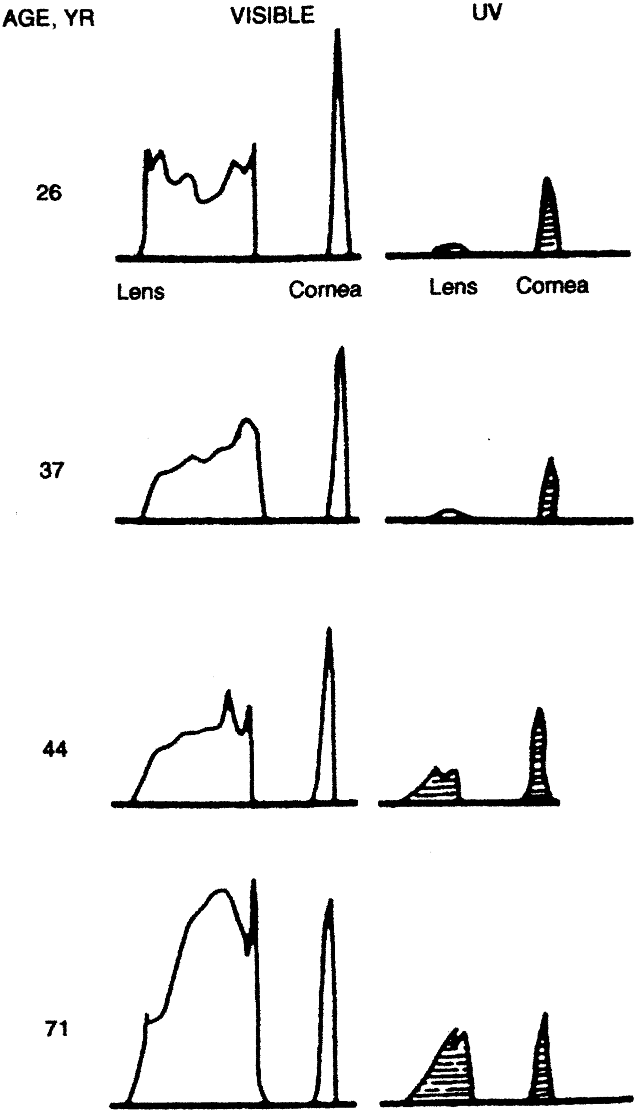

FIG. 5.11 UV densitometric analyses of the eye at different ages. Note increased fluorescence levels with age.

TABLE 5.17 Centigrade/Fahrenheit temperature conversions.

To °F	From	To °C	To °F	From	To °C
32.0	**0**	−17.8	221	**105**	40.6
41.0	**5**	−15.0	230	**110**	43.3
50.0	**10**	−12.2	239	**115**	46.1
59.0	**15**	−9.44	248	**120**	48.9
68.0	**20**	−6.67	257	**125**	51.7
77.0	**25**	−3.89	266	**130**	54.4
86.0	**30**	−1.11	275	**135**	57.2
89.6	**32**	0.00	284	**140**	60.0
95.0	**35**	+1.67	293	**145**	62.8
104	**40**	+4.44	302	**150**	65.6
113	**45**	+7.22	311	**155**	68.3
122	**50**	+10.0	320	**160**	71.1
131	**55**	+12.8	329	**165**	73.9
140	**60**	+15.6	338	**170**	76.7
149	**65**	+18.3	347	**175**	79.4
158	**70**	+21.1	356	**180**	82.2
167	**75**	+23.9	365	**185**	85.0
176	**80**	+26.7	374	**190**	87.8
185	**85**	+29.4	383	**195**	90.6
194	**90**	+32.2	392	**200**	93.3
203	**95**	+35.0	401	**205**	96.1
212	**100**	+37.8	410	**210**	98.9
			414	**212**	100.0

References

1. Ness, S., Holden, W. O., and Moss, C. E., "Need for Clarity in Military Standards Pertaining to Levels of Optical Radiation in Penetrant and Magnetic Particle NDT Inspection Processes," *Materials Evaluation,* Vol. 48, No. 3, American Society for Nondestructive Testing, Columbus, OH, 1990, pp. 354–365.
2. Holden, W. O., "UV / Black Light Measurement for NDT," *Materials Evaluation,* Vol. 41, No. 3, American Society for Nondestructive Testing, Columbus, OH, 1983, pp. 244, 246, 248, 249.

Standards Cited in this Chapter

AMS 2644A, *Inspection Materials, Penetrant,* SAE International, Warrendale, PA, May 2000.

AMS 2647B, *Fluorescent Penetrant Inspection, Aircraft and Engine Component. Maintenance,* SAE International, Warrendale, PA, October 1999.

ASTM E 165, *Standard Test Method for Liquid Penetrant Examination,* ASTM, West Conshohocken, PA.

ASTM E 1135, *Standard Test Method for Comparing the Brightness of Fluorescent Penetrants,* ASTM, West Conshohocken, PA.

ASTM E 1417, *Standard Practice for Liquid Penetrant Examination,* ASTM, West Conshohocken, PA.

Notes:

6

Magnetic Particle Testing

A. Units and Conversion Factors

TABLE 6.1 Units and conversion factors for magnetic particle testing.

Quantity	Symbol	SI Unit	Other Unit	Conversion
Illuminance		lux (lx) [1 lx = 1 lumen/m^2]	footcandle (fc)	1 fc ≈ 10.8 lx
Inductance	L	henry (H) [1 H = 1 Wb/A]		
Kinematic viscosity	v	mm^2/s	centiStokes (cSt)	1 cSt = 1 mm^2/s
Magnetic field strength	H	ampere per meter, A/m	oersted (Oe)	1 Oe = $1000/4\pi$ A/m
Coercive force	H_c	ampere per meter, A/m		
Magnetic flux	ϕ	weber (Wb) [1 Wb = 1 volt-second]	maxwell (Mx)	1 Mx = 10^{-8} Wb
Magnetic flux density (Magnetic induction)	B	tesla (T) [1 T = 1 Wb/m^2]	gauss (G)	1 G = 10^{-4} T
Saturation flux density	B_s	tesla (T)		
Magnetization	M	ampere per meter, A/m	gauss (G)	1 G = 1000 A/m
Permeability	μ	henry per meter, H/m		
Permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ H/m		
Relative permeability, μ/μ_0	μ_r	dimensionless		
Initial relative permeability	μ_i	dimensionless		
Maximum relative permeability	$\mu_{\max}$	dimensionless		
Temperature		°C	°F	(°F) = 1.8(°C) + 32

B. Magnetic Properties

TABLE 6.2 Magnetic properties of ferromagnetic materials at normal temperatures.

Material	Composition, %	Condition[A]	Initial Relative Permeability	Maximum Relative Permeability	Saturation Flux Density, T	Coercive Force from Saturation, A/m	Curie Point, °C	Ref.
Iron	99.95 Fe	Sheet, HT 1480 & 880	10000	>200000	2.15–2.16	4	770	[1,2][B]
	99.8 Fe	HT 950	150	5000	2.15	80	770	[3]
Ingot iron	99+ Fe		250	7000	2.16	80		[2]
Cast iron	Gray iron, low P	As cast		315				[4]
		Annealed		1560				[4]
	Gray iron, high P	As cast		281				[4]
		Annealed		760				[4]
	Whiteheart malleable	Pearlitic center		730				[4]
		Mainly ferritic		1455				[4]
	Blackheart malleable			2120				[4]
	Spheroidal graphite	Pearlitic		290				[4]
		Annealed ferritic		1150				[4]
	Spheroidal graphite, 0 Ni			2060				[4]
Silicon iron (<0.005 C)								
	0.5 Si	Sheet, HT 850	280	3000	2.14		765	[1]
	1.2 Si	Annealed sheet		6100	2.10			[2]
	1.5 Si		640	9350	2.09		760	[2]
	1.75 Si	Sheet, HT 850	280	5000	2.09		750	[1]
	2.8 Si	Annealed sheet		5800	2.04			[2]
	3.25 Si	Sheet, HT 850	290	8000	2.02		740	[1]
	3.3 Si		1250	9200	2.00		740	[2]

Continues on next page

TABLE 6.2 *continued.*

Material	Composition, %	Condition^A	Initial Relative Permeability	Maximum Relative Permeability	Saturation Flux Density, T	Coercive Force from Saturation, A/m	Curie Point, °C	Ref.
Silicon iron (<0.005 C)								
	3.75 Si	Annealed sheet		7000	1.99			[2]
	4 Si	Hot rolled	500	7000	2.0			[5]
	4.25 Si	Annealed sheet		9000	1.95			[2]
	4.6 Si		1250	9750	1.95		720	[2]
Carbon steel	0.1 C, 0.33 Si, 0.67 Mn	Cast		2100	1.95	128		[4]
	0.1 C, 0.33 Si, 0.67 Mn	Cast, annealed		2420	1.92	136		[4]
	0.1 C, 0.33 Si, 0.67 Mn	Cast, normalized		1950	1.96	168		[4]
	0.19 C, 0.3 Si, 0.48 Mn	Cast		1720	1.87	168		[4]
	0.19 C, 0.3 Si, 0.48 Mn	Cast, annealed		2100	1.88	156		[4]
	0.19 C, 0.3 Si, 0.48 Mn	Cast, normalized		1520	1.91	216		[4]
	0.19 C, 0.48 Si, 1.14 Mn	Cast, annealed		1300	1.86			[4]
	0.2 C	Wrought, HT 950	120	2000	2.12	140	770	[3,6]
	0.27 C, 0.25 Si	Cast, annealed		2500				[6]
	0.34 C, 0.44 Si, 0.55 Mn	Cast		840	1.87	440		[4]
	0.34 C, 0.44 Si, 0.55 Mn	Cast, annealed		1200	1.85	296		[4]
	0.34 C, 0.44 Si, 0.55 Mn	Cast, normalized		970	1.87	440		[4]
	0.9C	Hot rolled		100	2.0			[7]

Continues on next page

TABLE 6.2 *continued.*

Material	Composition, %	Condition^A	Initial Relative Permeability	Maximum Relative Permeability	Saturation Flux Density, T	Coercive Force from Saturation, A/m	Curie Point, °C	Ref.
AISI 1006	0.08 C, 0.1–0.4 Si, 0.3–0.5 Mn	Wrought		2400–5000	1.96	40–120		[4]
AISI 1021	0.16–0.24 C, 0.5–0.9 Mn	Wrought		1100	1.96	240–400		[4]
AISI 1030	0.26–0.34 C, 0.6–1.0 Mn	Wrought		1000	1.88	800		[4]
AISI 1055	0.5–0.6 C, 0.5–0.9 Mn	Wrought		400	1.81	1200		[4]
AISI 1095	1 C, 0.5 Mn	Quenched					770	[6]
Cobalt steel	17 Co + W + Cr	Quenched					840	[6]
	36 Co, 3.8 W, 5.8 Cr, 0.8 C	Quenched					890	[6,8]
Chromium steel	3.5 Cr, 1 C						745	[8]
	3 Cr, 0.1–0.4 Si, 0.2–0.6 C	Wrought		680	1.75–1.85	880		[4]
Cr-Mo steel	1.2 Cr, 0.4 Mo, 0.7 Mn, 0.3 C	HT 925, 880, & 700			1.76			[4]
Manganese steel								
AISI 1119	1.1 Mn, 0.3 Si, 0.15 C	Wrought		1200	1.95	200–400		[4]
	1.14 Mn, 0.48 Si, 0.19 C	Annealed 925°C		1300	1.86			[4]
	1.37 Mn, 0.52 Si, 0.31 C	HT 950, 860, & 629		750	1.70			[4]
AISI 1526	1.40 Mn, 0.29 Si, 0.29 C	HT 950, 880, & 600		650	1.78			[4]

Continues on next page

TABLE 6.2 *continued.*

Material	Composition, %	Condition^A	Initial Relative Permeability	Maximum Relative Permeability	Saturation Flux Density, T	Coercive Force from Saturation, A/m	Curie Point, °C	Ref.
Nickel steel	3 Ni, 1 Cr, 0.1–0.4 Si, 0.2–0.6 C	Wrought		600	1.85–1.95	980		[4]
Silicon steel								
	0.35–2.00 Si, 0.2 Mn, 0.1 C	Cast, annealed		14800	2.14			[9]
	1.1 Si, $<$0.04 C	HT 845 & 540		14800	2.10		761	[10]
	2.3 Si, $<$0.04 C	HT 845 & 540		11200	2.06		748	[10]
	2.5 Si, 3 C	Cast		230				[6]
	4.0 Si, $<$0.04 C	HT 845 & 540		9000	2.00		728	[10]
	4.5 Si	Hot rolled				40		[2]
	6 Si, 2.6 C	Cast		1020				[6]
Stainless steel	12–20 Cr, $<$3 Ni, $<$1 Mn, $<$0.35 C	Wrought		660	1.43–1.64	400–1250		[4]
AISI 410	12 Cr, 0.15 max C	Annealed		800–900				[2,11]
AISI 416	12 Cr, 0.15 max C, 0.07 S	Hardened		76				[2]
AISI 420	12 Cr, 0.15 min C	Annealed		674				[2]
AISI 420	12 Cr, 0.15 min C	Hardened		71				[2]
AISI 430	16 Cr, 0.12 max C	Annealed		400				[11]
AISI 430	17 Cr, 0.12 max C	Hardened		278				[2]
AISI 440B	17 Cr, 0.85 C	Annealed		420				[2]
AISI 440B	17 Cr, 0.85 C	Hardened		26				[2]

Continues on next page

TABLE 6.2 *continued.*

Material	Composition, %	Condition[A]	Initial Relative Permeability	Maximum Relative Permeability	Saturation Flux Density, T	Coercive Force from Saturation, A/m	Curie Point, °C	Ref.
17-4 PH	17 Cr, 4 Ni, 1 Mn, 1 Si, 0.7 C	Annealed		95				[12]
17-4 PH	17 Cr, 4 Ni, 1 Mn, 1 Si, 0.7 C	Hardened		151				[12]
17-7 PH	17 Cr, 7 Ni, 1 Mn, 1 Si, 0.9 C	Hard temper		125				[12]
Tungsten steel	6 W, 1 Cr, 1 C	Quenched					660	[6]
	6 W, 0.5 Cr, 0.7 C						760	[8]
Iron carbide	Cementite, Fe_3C				1.24		215	[13]
Iron oxides	Ferric oxide, Fe_2O_3, rust	Pressed 1100–1200°C		9200			620	[3,6]
	γ-Fe_2O_3, brown iron oxide						470	[5]
	Ferrosoferric oxide, Fe_3O_4 (black iron oxide, magnetite)	Pressed 1100–1200°C	5	25	0.6		575	[3,6]
Cobalt	99 Co	HT 1000	70	250	1.79–1.82	800	1120	[2,3]
Nickel	99 Ni	HT 1000	110	600	0.61	60	358	[3]
Nickel alloys	4.8 Mn						260	[11]
	1 Si						320	[7]
	5 Si						45	[7]

[A] HT = heat treated at the indicated temperatures, °C.

[B] Numerals in brackets designate references listed at the end of the chapter.

C. Magnetization

C.1 Minimum Flux Density

Minimum flux density in the component surface should be 1 T in order to assure acceptable magnetic particle testing. A steel is considered to be magnetic if this flux density is achieved with a magnetic field strength of 2.4 kA / m (ISO 4986)[1]. This means that it will have a relative permeability greater than 300 [14]. In low-alloy and low-carbon steels with high relative permeabilities, this flux density is achieved with a tangential field of 2 kA / m or less according to ISO 9934-1, and ISO 6933 only requires a field strength of 2 kA / m parallel to the main flux direction at any spot in the area to be inspected.

ASTM E 1444 recommends use of a Hall effect probe gaussmeter to verify peak value tangential field strengths of 2.4 to 4.8 kA / m (30 to 60 G). Alternatively, the following formulas may be used to estimate the levels of electric current required to produce adequate magnetization.

C.2 Longitudinal Magnetization with Low-Fill Factor Coils

Longitudinal magnetization with low-fill factor coils where the cross-sectional area of the coil is ten or more times the cross-sectional area of the part being inspected:

(1) For parts positioned to the side of the coil, ASTM E 1444 specifies

$$NI = 45\,000/(L/D) \qquad (\pm 10\%) \tag{6.1a}$$

where N = number of coil turns,
I = current in amperes through the coil,
L = length of the part, and
D = diameter of the part, and $2 < (L/D) < 15$.

ISO 9934-1 specifies

$$NI = 0.4H\cdot K/(L/D) \tag{6.1b}$$

---

[1] Standards cited in this chapter are listed at the end of the chapter.

where H = tangential field in kA / m,
K = 22 000 for rms ac or full-wave rectified current, or
= 11 000 for half-wave rectified current,
D = diameter of the part for circular cylinders, or
= perimeter / π for non-circular cylinders and shapes, and $5 < (L / D) < 20$.

The *ASME Boiler & Pressure Vessel Code* (the "Boiler Code")[2] [15] specifies

$$NI = 35\,000 / [(L / D) + 2] \qquad (\pm 10\%) \qquad (6.1c)$$

for $(L / D) \geq 4$, and Eq 1a for $2 \leq (L / D) < 4$. For large parts, due to size and shape, the Boiler Code further specifies that $1200 \leq (NI) \leq 4500$.

(2) For parts positioned in the center of the coil, ASTM E 1444 specifies

$$NI = KR / [(6L / D) - 5] \qquad (\pm 10\%) \qquad (6.1d)$$

where R = radius of the coil, mm (or in.),
K = 1690 ampere-turns per mm if R is measured in mm, or
= 43 000 ampere-turns per in. if R is measured in inches, and $2 < (L / D) < 15$.

C.3 Longitudinal Magnetization with Cable Wrap or High-Fill Factor Coils

Longitudinal magnetization with cable wrap or high-fill factor coils where the cross-sectional area of the coil is less than twice the cross-sectional area—including hollow portions—of the part being tested. ASTM E 1444 specifies

$$NI = 35\,000 / [(L / D) + 2] \qquad (\pm 10\%) \qquad (6.2a)$$

for $2 < (L / D) < 15$. If the part has hollow portions, replace D with D_{eff} as follows:

$$D_{\mathrm{eff}} = 2[(A_t - A_h) / \pi^{1/2} \qquad (6.2b)$$

---

[2] Boiler Code requirements for magnetic particle testing generally follow ASTM E 709.

where A_t = total cross-sectional area of the part, and
A_h = total cross-sectional area of the hollow portions.

For circular cylindrical parts this reduces to

$$D_{\text{eff}} = [(OD^2 - (ID)^2]^{1/2} \tag{6.2c}$$

where OD = outside diameter of the cylinder, and
ID = inside diameter of the cylinder.

For longitudinal magnetization of small parts, ASTM A 275 and the Boiler Code both specify Eq 1c where $L/D \geq 4$, while for large parts use 1200 to 4500 ampere turns. For $2 \leq (L/D) \leq 4$ the Boiler Code further specifies Eq 1a.

Where the component fills the coil, ISO 9934-1 specifies:

$$I = 3H(T + W^2/4T) \text{ for rectified current and} \tag{6.2d}$$

$$I = 3H(10 + W^2/40) \text{ for alternating current} \tag{6.2e}$$

where I = rms amperes,
H = tangential field in kA/m,
T = wall thickness of part, or radius of the solid circular cylinder, in mm, and
W = spacing between adjacent windings in the coil, mm.

C.4 Longitudinal Magnetization for Intermediate-Fill Factor Coils

Longitudinal magnetization for intermediate-fill factor coils where the cross-sectional area of the coil is between two and ten times the cross-sectional area of the part being inspected. ASTM E 1444 specifies:

$$NI = (NI)_h(10 - Y)/8 + (NI)_t(Y - 2)/8 \tag{6.3}$$

where $(NI)_t$ = value of NI calculated with Eq 1a,
$(NI)_h$ = value of NI calculated with Eq 2a, and
Y = ratio of the cross-sectional area of the coil to the cross-sectional area of the part.

C.5 Circular Magnetization of Simple-Shaped Components or Parts Using Axial Current Flow

ISO 9934-1 gives the following formula to provide adequate magnetization:

$$I = H \cdot p \qquad (6.4)$$

where I = current in amperes,

H = tangential field in kA / m, and

p = component perimeter in mm.

The *Nondestructive Testing Handbook* (the "NDT Handbook") [7] limits this formula to direct current.

When passing current directly through the part, the recommended current levels per unit of maximum part diameter are as follows:

Max Part Diameter	ASTM A 275	ASTM E 1444^{A} & Boiler Code
Up to 5 in. (125 mm)	600 to 900 A/in. (25 to 35 A/mm)	300 to 800 A/in. (12 to 32 A/mm)
5 to 10 in. (125 to 250 mm)	400 to 600 A/in. (15 to 25 A/mm)	300 to 800 A/in. (12 to 32 A/mm)
Over 10 in. (250 mm)	100 to 400 A/in. (4 to 15 A/mm)	300 to 800 A/in. (12 to 32 A/mm)

^{A}In special cases, currents up to 1000 A/in. (40 A/mm) may be required.

C.6 Indirect Circular Magnetization of Hollow Parts

If the conductor is placed against an inside wall of the part, ASTM E 1444 takes the effective diameter as the diameter of the conductor plus twice the wall thickness, while for ASTM A 275 the effective diameter is simply the wall thickness. For indirect circular magnetization of the bores of shaft forgings, ASTM A 275 specifies 100 to 125 A / in. (4 to 5 A / mm) of bore diameter.

For indirect circular magnetization using through coils rather than a solid conductor, use the current specified for direct magnetization divided by the number of turns (ASTM A 275 and the Boiler Code).

C.7 Prods Current Flow

ISO 9934-1 gives

$$I = 2.5H \cdot d \qquad (6.5)$$

where d = prod spacing in mm, and $d < 200$.

ASTM E 1444 requires prod spacing to be between 2 and 8 in. (50 and 200 mm), ASTM A 275 requires prod spacing to be between 3 and 8 in. (75 and 200 mm), and the Boiler Code specifies that prod spacing shall not exceed 8 in. (203 mm). Recommended current levels per unit of prod spacing are as follows:

Material Thickness	ASTM E 1444	ASTM A 275	Boiler Code
Less than 3/4 in. (19 mm)	90 to 115 A/in. (3.5 to 4.5 A/mm)	75 to 100 A/in. (3 to 4 A/mm)	90 to 110 A/in.
More than 3/4 in. (19 mm)	100 to 125 A/in. (4.0 to 5.0 A/mm)	100 to 125 A/in. (4 to 5 A/mm)	100 to 125 A/in.

The requirements of ASTM A 966 are similar to those of ASTM A 275 except that prod spacing shall not exceed 6 in. (150 mm).

C.8 Induced Current Flow

ISO 9934-1 gives

$$I_{\text{ind}} = H \cdot p \tag{6.6}$$

where I_{ind} = current in amperes.

C.9 Adjacent Conductor

ISO 9934-1 gives

$$I = 4\pi \cdot d \cdot H \tag{6.7}$$

where d is the distance of the cable from the part surface, and also the width of the test area on each side of the cable center line, in mm.

D. Testing Parameters

D.1 Illumination

For visible particles, wet or dry, the NDT Handbook [7] states that illumination between 300 and 1000 lx (30 and 100 fc) is best for most applications. The minimum light intensity at the test surface is specified as follows:

ASTM E 1444 & A 966	ISO 6933 & 9934-1	ISO 13664 & 13665
1000 lx	500 lx	350 lx

For fluorescent particles, the following table gives the specified minimum ultraviolet light intensity and the maximum visible light intensity at the test surface.

Standard	Specified UV Radiation	Minimum UV Intensity	Maximum Visible Light Intensity
ASTM A 275	3300 to 3900 Å (330–390 nm)	1000 μW/cm^2 (Note A)	
ASTM A 966			20 lx
ASTM E 1444	“black light”	1000 μW/cm^2	20 lx
Boiler Code	“black light”	1000 μW/cm^2	
ISO 3059	UV-A (315–400 nm)	1000 μW/cm^2	20 lx
ISO 6933	365 nm	500 μW/cm^2	20 lx
ISO 9934-1	UV-A	1000 μW/cm^2	20 lx
ISO 13664 & 13665	UV-A	800 μW/cm^2	20 lx

Note A: At a distance of 15 in. (375 mm) from the lamp.

D.2 Particles

ASTM E 1444 specifies that magnetic particles shall satisfy specifications AMS 3040 through 3046, which call for 98% by weight to pass through US Standard No. 80 sieve,[1] which is equivalent to a particle size of 180 μm (0.007 in.), whether intended for use in the dry method or the wet method.

Dry method: For pipe testing the NDT Handbook reports a proposal that 75 wt% of dry powder should be finer than 120 mesh ASTM sieve size[2] (125 μm, 0.005 in.) and at least 15% should be finer than 325 mesh (45 μm, 0.0017 in.). The NDT Handbook also states that a sensitive dry powder contains about 35 wt% particles in the 25- to 50-μm (0.001- to 0.002-in.) diameter range. The Boiler Code [15] states that magnetic particle testing with dry particles shall not be performed if the surface temperature of the part exceeds 600°F (316°C).

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[1] The USA Standard Sieve Series is specified in ASTM E 11. A portion of that series that is applicable to magnetic particle testing is reproduced in Table 6.3.

[2] “ASTM sieve size” is a misnomer for the USA Standard Sieve Series.

TABLE 6.3 U.S.A. standard sieve series (from ASTM E 11).

	Nominal Sieve Opening	
Sieve No.	μm	in.
70	212	0.0083
80	180	0.0070
100	150	0.0059
120	125	0.0049
140	106	0.0041
170	90	0.0035
200	75	0.0029
230	63	0.0025
270	53	0.0021
325	45	0.0017
400	38	0.0015
450	32	0.0012
500	25	0.0010
635	20	0.0008

Wet method: The compositions include black iron oxide or magnetite (Fe_3O_4), brown iron oxide (γ-Fe_2O_3), and red iron oxide (α-Fe_2O_3). Most non-fluorescent particles are uncolored black or brown oxides [16].

Wet particles range in size from 0.1 to 60 μm (0.000004 to 0.0025 in.) according to Bray and Stanley [17] and Betz [16]. However, the NDT Handbook says that sensitive wet particles range from 5 to 15 μm (0.0002 to 0.0006 in.) in diameter and that unpigmented ferromagnetic oxide particles are an order of magnitude finer. AMS 3044 to 3046 specify that the particles be fluorescent in the yellow-green range.

D.3 Sensitivity

ASTM E 1444 specifies that particles shall show the following indications in the ANSI KETOS tool steel ring test:

Particles Used	Central Conductor FWDC Amperage	Minimum No. of Holes Indicated
Wet suspension	1400	3
	2500	5
	3400	6
Dry powder	1400	4
	2500	6
	3400	7

AMS 3040 through 3046 specify the following indications in the tool steel ring test using 2500 A of direct current. (The tool steel ring is described in SAE AS5282, which further specifies that the current shall be full-wave rectified alternating current.)

AMS Standard	Particles	Minimum Number of Holes Indicated
3040	Dry, visible	8
3041, 3042, 3043	Wet suspension, visible	6
3044, 3045	Wet suspension, fluorescent	7
3046	Wet suspension, fluorescent	5

Dry particles are considerably more sensitive to subsurface discontinuities. According to the NDT Handbook, dry particles may be effective for discontinuities up to 6 mm (0.25 in.) below the surface, while wet particles are rarely useful for discontinuities more than 0.2 mm (0.008 in.) below the surface.

In situations where multidirectional magnetization is required, a variety of artificial flaws is described in ASTM E 1444 and SAE AS5371 for verifying that the magnetic field is balanced in all directions.

D.4 Suspension Vehicles

ASTM E 1444 requires suspension vehicles for the wet method to conform to AMS 2641 or be water conditioned for proper wetting. SAE AS4792 specifies that water conditioning agents have a pH between 7 and 10, and ASTM E 1444 requires that conditioned water have a pH between 6 and 10. ASTM A 275 permits clean water or water with wetting agents. ISO 6933 limits suspension vehicles to kerosene or water with anticorrosives and wetting agents.

Requirements for the viscosity, density, flash point, and some other properties of oil vehicles are given in Table 6.4.

TABLE 6.4 Property requirements of suspension vehicles.

Standard	Viscosity at 38°C (100°F)	Viscosity at Bath Temperature	API Gravity[A]	Flash Point °C (°F)	Particulate Matter	ASTM Color[B]	Total Acid Number
AMS 2641	<3.0 mm^2/s	<5.0 mm^2/s		Type 1: >93 (200) Type 2: 60–93 (140–200)	≤1.0 mg/L	≤No. 2	≤0.15 mg/L KOH[C]
AMS 3161	30–32 SUS[D] (1.2–1.8 mm^2/s)		46–50°	>66 (150)			
ASTM A 275	31 SUS (1.5 mm^2/s)		46°				
A-A-59230	<3.0 mm^2/s	<5.0 mm^2/s		>93 (200)	≤0.5 mg/L	≤No. 1	≤0.015 mg/g KOH

[A] API gravity per ASTM D 1298. The conversion from API gravity to specific gravity in the range applicable to magnetic particle testing is given in Table 6.5

[B] Determined in accordance with ASTM D 1500.

[C] KOH is potassium hydroxide.

[D] The conversion from SUS (Saybolt Universal Seconds) viscosity to kinematic viscosity in the range applicable to magnetic particle testing is given in Table 6.6.

TABLE 6.5 °API/Specific gravity conversion.

API Gravity, Degrees	Specific Gravity at 60°F
41	0.820
42	0.816
43	0.811
44	0.806
45	0.802
46	0.797
47	0.793
48	0.788
49	0.784
50	0.780
51	0.775
52	0.771
53	0.767
54	0.763
55	0.759
56	0.755
57	0.751
58	0.747
59	0.743
60	0.739

TABLE 6.6 Conversion of SUS viscosity to kinematic viscosity.[A,B]

SUS Viscosity		Equivalent Kinematic Viscosity	SUS Viscosity		Equivalent Kinematic Viscosity
At 100°F (37.8°C)	At 210°F (98.9°C)	(±0.01), mm²/s	At 100°F (37.8°C)	At 210°F (98.9°C)	(±0.01), mm²/s
30.0	30.2	1.22	32.5	32.7	1.97
30.1	30.3	1.25	32.6	32.8	2.00
30.2	30.4	1.28	32.7	32.9	2.03
30.3	30.5	1.31	32.8	33.0	2.06
30.4	30.6	1.34	32.9	33.1	2.09
30.5	30.7	1.37	33.0	33.2	2.12
30.6	30.8	1.40	33.1	33.3	2.15
30.7	30.9	1.43	33.2	33.4	2.18
30.8	31.0	1.46	33.3	33.5	2.21
30.9	31.1	1.49	33.4	33.6	2.24
31.0	31.2	1.52	33.5	33.7	2.26
31.1	31.3	1.55	33.6	33.8	2.29
31.2	31.4	1.58	33.7	33.9	2.32
31.3	31.5	1.61	33.8	34.0	2.35
31.4	31.6	1.64	33.9	34.1	2.38
31.5	31.7	1.67	34.0	34.2	2.41
31.6	31.8	1.70	34.1	34.3	2.44
31.7	31.9	1.73	34.2	34.4	2.47
31.8	32.0	1.76	34.3	34.5	2.50
31.9	32.1	1.79	34.4	34.6	2.53
32.0	32.2	1.82	34.5	34.7	2.56
32.1	32.3	1.85	34.6	34.8	2.59
32.2	32.4	1.88	34.7	34.9	2.62
32.3	32.5	1.91	34.8	35.0	2.65
32.4	32.6	1.94	34.9	35.1	2.68

[A] Adapted from ASTM D 2161-93.

[B] SUS viscosity is not defined for values below 32.0. Equivalent kinematic viscosities in this table for SUS values below 32.0 were estimated by extrapolation.

D.5 Suspensions

Particle concentrations by volume percent are specified as follows:

Particle Type	ASTM E 1444	ASTM A 275	AMS 3041, 3043, 3045, 3046
visible	1.2 to 2.4%	1.0 to 2.0% in oil 2.0 to 2.5% in water	1.5 to 2.4%
fluorescent	0.1 to 0.4%	0.1 to 0.7%	0.2 to 0.5%

The Boiler Code specifies that for magnetic particle testing with wet particles the temperature of the suspension and the surface of the part shall not exceed 135°F (57°C).

D.6 Coatings

ASTM E 1444 specifies that magnetic particle testing shall not be performed with nonmagnetic coatings (e.g., paint) in place that exceed 0.003 in. (0.08 mm) in thickness, or ferromagnetic coatings (e.g., electroplated nickel) that exceed 0.001 in. (0.03 mm) in thickness.

D.7 Current Types **(ASTM E 1444)**

Half-wave rectified alternating current is best for the dry particle method. For defects open to the surface use alternating current only. When using the wet particle method for subsurface defects, use full-wave rectified alternating current.

D.8 Yokes[3]

ASTM E 1444 requires alternating current yokes to have a lifting force of at least 10 lb (45 N) with a 2- to 4-in. (50- to 100-mm) spacing between the legs. Direct current yokes shall have a lifting force of at least 30 lb (135 N) with a 2- to 4-in. (50- to 100-mm) spacing between the legs, or 50 lb with a 4- to 6-in. (100- to 150-mm) spacing between the legs.

ASTM A 275 allows pole spacings from 2 to 8 in. (50 to 200 mm). Direct current yokes are required to have a lifting power of at least 40 lbf (175 N) at a pole spacing of 3 to 6 in. (75 to 150 mm).

The Boiler Code requires an alternating current yoke to have a lifting power of at least 10 lb (4.5 kg) at the maximum pole spacing that will be used. A direct current or permanent magnet

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[3] The units used in this section are inconsistent but are quoted directly from the cited standards. Strictly speaking, the *force* exerted by a yoke to lift a given weight should be expressed in pounds-force (lbf) or newtons (N), while the *mass* of the weight should be expressed in pounds (lb) or kilograms (kg).

yoke shall have a lifting power of at least 40 lb (18.1 kg) at the maximum pole spacing that will be used.

E. Demagnetizing Factors

TABLE 6.7 Demagnetizing factors for rods [1].

Dimensional Ratio, Length/Diameter	Demagnetizing Factor, $N/4\pi$
0	1.0
1	0.27
2	0.14
5	0.040
10	0.0172
20	0.00617
50	0.00129
100	0.00036
200	0.000090
500	0.000014
1000	0.0000036
2000	0.0000009

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ASTM Standards Cited in this Chapter

A 275 / A275M, Standard Test Method for Magnetic Particle Examination of Steel Forgings
A 867 / A867M, Standard Specification for Iron-Silicon Relay Steels
A 966 / A966M, Standard Test Method for Magnetic Particle Examination of Steel Forgings Using Alternative Current
D 1298, Standard Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method
D 1500, Standard Test Method for ASTM Color of Petroleum Products (ASTM Color Scale)
D 2161, Standard Practice for Conversion of Kinematic Viscosity to Saybolt Universal Viscosity or to Saybolt Furol Viscosity
E 11, Standard Specification for Wire Cloth and Sieves for Testing Purposes
E 709, Standard Guide for Magnetic Particle Examination
E 1444, Standard Practice for Magnetic Particle Examination

SAE Standards Cited in this Chapter

AMS 2641A, Vehicle, Magnetic Particle Inspection, Petroleum Base, Aug 1996
AMS 2644A, Inspection Material, Penetrant, May 2000
AMS 2647B, Fluorescent Penetrant Inspection, Aircraft and Engine Component Maintenance, Oct 1999
AMS 3040B, Magnetic Particles, Nonfluorescent, Dry Method, Dec 1995
AMS 3041C, Magnetic Particles, Nonfluorescent, Wet Method, Oil Vehicle, Ready-to-Use, Aug 1996
AMS 3042C, Magnetic Particles, Nonfluorescent, Wet Method, Dry Powder, Aug 1996
AMS 3043B, Magnetic Particles, Nonfluorescent, Wet Method, Oil Vehicle, Aerosol Packaged, Aug 1996
AMS 3044D, Magnetic Particles, Fluorescent, Wet Method, Dry Powder, Aug 1996
AMS 3045C, Magnetic Particles, Fluorescent, Wet Method, Oil Vehicle, Ready-to-Use, Aug 1996
AMS 3046D, Magnetic Particles, Fluorescent, Wet Method, Oil Vehicle, Aerosol Packaged, October 1998
AMS 3161A, Oil, Odorless, Heavy Solvent, Oct 1993
SAE AS4792, Water Conditioning Agents for Aqueous Magnetic Particle Inspection, 1993-01
SAE AS5282, Tool Steel Ring for Magnetic Particle Inspection, 1998-03
SAE AS5371, Reference Standards, Notched Shims for Magnetic Particle Inspection, 1998-03

ISO Standards Cited in this Chapter

ISO 3059:2001, Non-Destructive Testing—Penetrant testing and magnetic particle testing—Viewing conditions
ISO 4986:1992, Steel castings—Magnetic particle inspection
ISO 6933:1986, Railway rolling stock material—Magnetic particle acceptance testing
ISO / FDIS 9934-1, Non-destructive testing—Magnetic particle testing—Part 1: General principles, 2000-09
ISO 13664:1997, Seamless and welded steel tubes for pressure purposes—Magnetic particle inspection of the tube ends for the detection of laminar imperfections
ISO 13665:1997, Seamless and welded steel tubes for pressure purposes—Magnetic particle inspection of the tube body for the detection of surface imperfections

Federal Specification Cited in this Chapter

Commercial Item Description A-A-59230, Fluid, Magnetic Particle Inspection, Suspension, 2 July 1998

Notes:

DS68-EB/Feb. 2002

7

Leak Testing

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[1] National Institute of Standards and Technology, Gaithersburg, MD 20899.

[2] Numerals in square brackets designate references listed at the end of the chapter. Figures and tables without designated references are the authors' own.

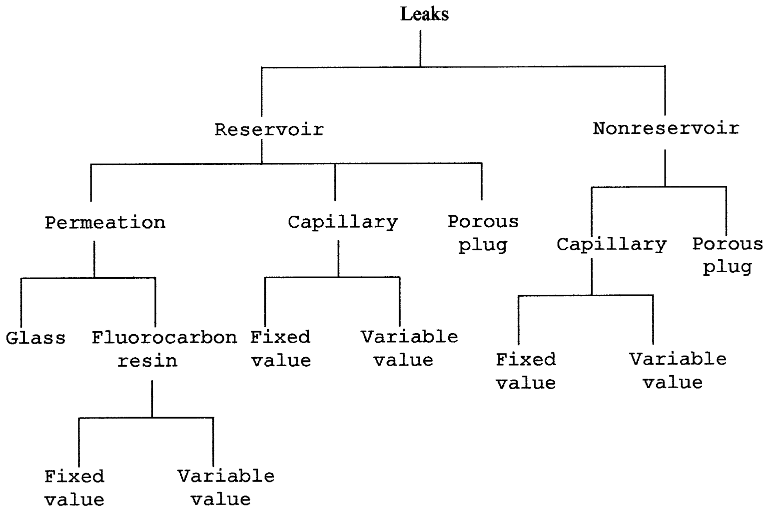

FIG. 7.1 Categories of artificial physical leaks commonly spoken of as "reference," "calibration," or "standard" leaks.

TABLE 7.1 Some characteristics of leak element types.

Leak Element	Gases	Linear Temperature Coefficient, %/K	Flow Rate Range, mol/s
Permeation			
Glass	Helium	2–7	10^{-15}–10^{-9}
Paladium	Hydrogen	3–7	
Plastic	Water SO_2, NO_2	10–20	10^{-13}–10^{-8}
Physical	Any[A]		10^{-13}–10^{-6}
Capillary		<0.5	
Crimped tube		<0.3	
Sintered			
Orifice		<0.3	

[A] Must not coat or react with the leak element.

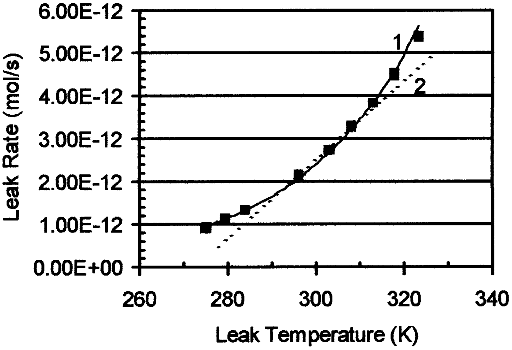

FIG. 7.2 Temperature dependence of leakage rate from a helium permeation leak. Line 1—exponential fit to data. Line 2—linear least squares fit from 283 to 308 K. Note: °C = K − 273.15.

TABLE 7.2 Temperature coefficients (measured by the National Institute of Standards and Technology) and corresponding glass types for helium permeation leaks.

Temperature Coefficient, K	Linear Temperature Coefficient, %/°C	Probable Glass Type
≤2500	3.5	Borosilicate
2700	3.7	Fused Silica
3000	4.1	Pyrex® 7740
3600	5.0	Corning® 7052

$$\mathbf{Q}_m = \mathbf{AT}\exp(-\mathbf{E}/\mathbf{RT})$$

where

$\mathbf{Q}_m$ is the molar leakage rate (in mol/s)

A is a constant

T is the absolute temperature (in K)

E is the diffusivity activation energy

R is the ideal gas constant

Sometimes the expression $\mathbf{B} = \mathbf{E}/\mathbf{R}$ is used, where **B** is referred to as the "temperature coefficient," and has units of absolute temperature (K). Near the calibration temperature, a linear approximation may be used:

$$\mathbf{Q}_m = \mathbf{Q}_{cal}[1 + \alpha(\mathbf{T} - \mathbf{T}_{cal})]$$

where

$\mathbf{Q}_m$ is the molar leakage rate (in mol/s) at the temperature **T**

$\mathbf{Q}_{cal}$ is the molar leakage rate at the calibration temperature $\mathbf{T}_{cal}$

α is the "linear temperature coefficient" and has units of inverse temperature $(K)^{-1}$.

FIG. 7.3 Helium permeation leak equations.

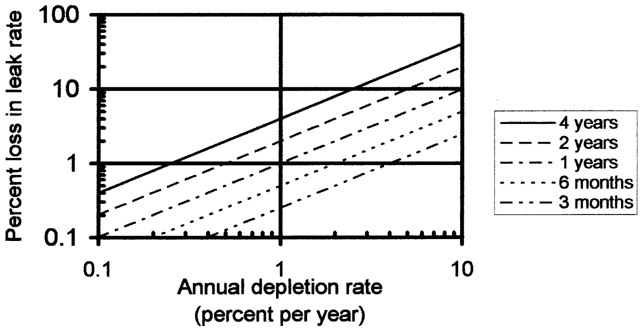

FIG. 7.4 Decline in leak rate as a function of annual depletion rate. (Percent loss) = (Annual depletion rate) *(Time since calibration).

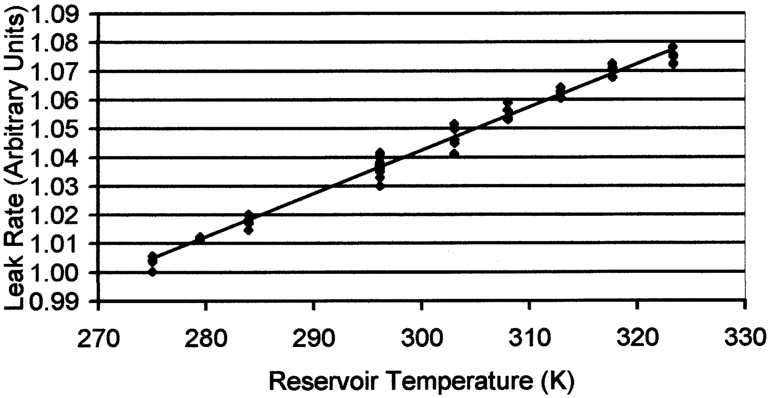

FIG. 7.5 **Data illustrating typical linear temperature dependence of a metal capillary leak. Note: °C = K − 273.15.**

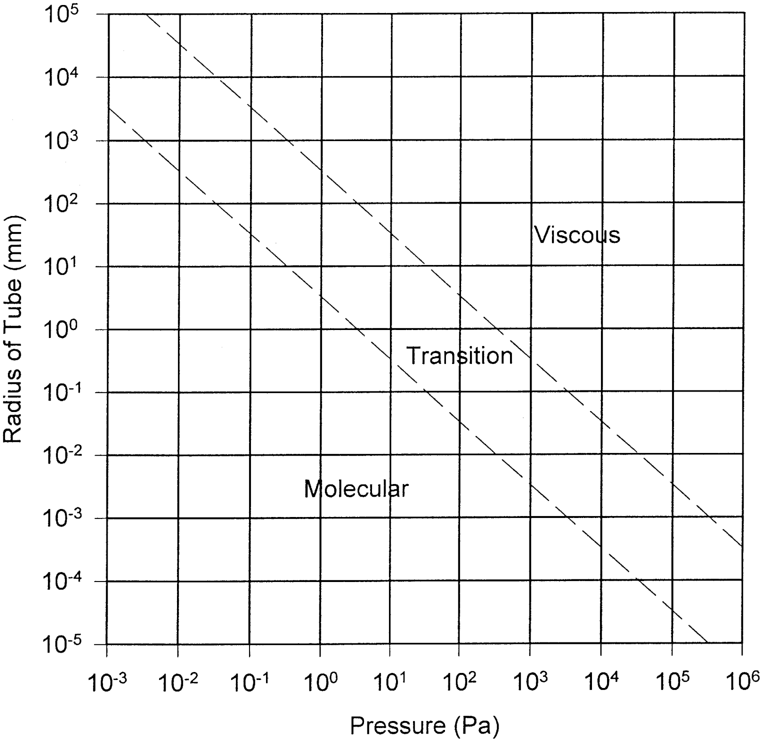

FIG. 7.6 Conditions for viscous, molecular, and transitional flow of gases through leaks at 298.15 K.

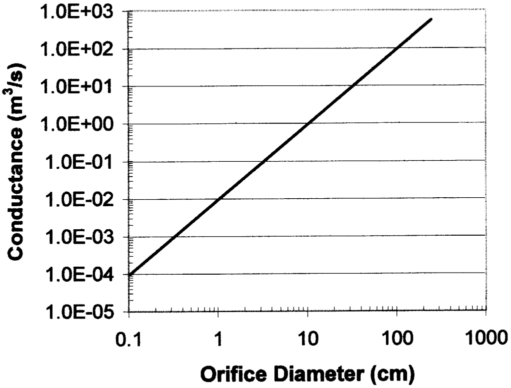

FIG. 7.7 Conductance of orifices for air at 293.15 K under molecular flow conditions.

TABLE 7.3 Comparison of molecular flow rates, Q_m, of other gases with helium molecular flow rate.

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To Convert To:	Multiply Helium Molecular Flow By:
Q_m of helium	1.00
Q_m of argon	0.316
Q_m of neon	0.447
Q_m of hydrogen	1.41
Q_m of nitrogen	0.374
Q_m of air	0.374
Q_m of water vapor	0.469

TABLE 7.4 Comparison of viscous flow rates, Q_v, of other gases with helium viscous flow rates.

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To Convert to:	Multiply Helium Viscous Flow By:
Q_v of helium	1.00
Q_v of argon	0.883
Q_v of neon	0.626
Q_v of hydrogen	2.23
Q_v of nitrogen	1.12
Q_v of air	1.08
Q_v of water vapor	2.09

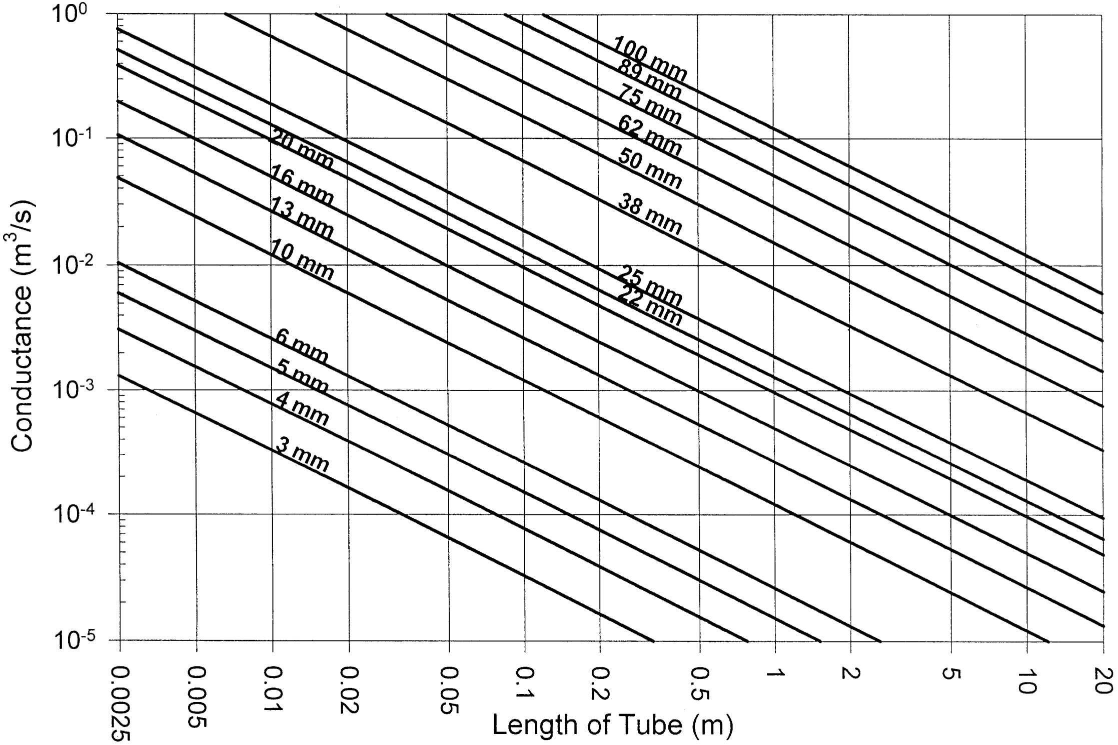

FIG. 7.8 Molecular flow conductance of cylindrical tubes of different lengths and inside diameters for air at 293.15 K. Inside diameters are printed on their respective curves.

TABLE 7.5 Physical properties of some common tracer gases and pressurizing gases used in leak testing.

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Gas	Formula	Molecular Weight, g/mol	Density at 101.325 kPa and 25°C, kg/m³	Viscosity at 101.325 kPa and 25°C, μPa · s	100 Pa Density at 25°C, g/m³	Thermal Speed at 25°C, m/s	Mean Free Path at 100 Pa and 25°C, μm	Molecular Diameter at 25°C, pm
Acetone	C_3H_6O	58.08		7.73	2.34	330	20.4	674
Acetylene	C_2H_2	26.04	1.077	10.26	1.06	492	40.1	481
Air		28.98	1.184	18.36	1.169	467	68.5	368
Ammonia	NH_3	17.03	0.703	10.20	0.694	609	49.2	434
Argon	Ar	39.94	1.634	22.77	1.613	398	72.3	358
Benzene	C_6H_6	30.07		7.60	3.15	284	17.3	732
Carbon dioxide	CO_2	44.01	1.811	14.90	1.79	379	44.9	454
Carbon monoxide	CO	28.01	1.145	17.72	1.13	475	67.3	371
Ethane	C_2H_6	30.07	1.243	9.39	1.23	458	34.0	522
Ethyl Alcohol	C_2H_6O	46.07		8.94	1.86	370	26.5	592
Ethylene	C_2H_4	28.05	1.155	10.33	1.14	474	38.9	488
Halocarbon								
R-11	CCl_3F	137.371	5.840	10.89	5.76	214	18.0	718
R-12	CCl_2F_2	120.914	5.045	12.52	4.98	228	22.4	643
R-21	$CHCl_2F$	102.92	4.284	11.56	4.23	248	22.5	642
R-22	$CHClF_2$	86.469	3.588	12.91	3.54	270	27.5	580
R-113	$C_2Cl_3F_3$	187.376		10.30	7.56	184	15.1	783

Continues on next page

TABLE 7.5 *continued.*

Gas	Formula	Molecular Weight, g/mol	Density at 101.325 kPa and 25°C, kg/m^3	Viscosity at 101.325 kPa and 25°C, μPa · s	100 Pa Density at 25°C, g/m^3	Thermal Speed at 25°C, m/s	Mean Free Path at 100 Pa and 25°C, μm	Molecular Diameter at 25°C, pm
Helium	He	4.003	0.164	19.80	0.1619	1256	198.0	216
Hydrogen	H	2.016	0.082	8.90	0.0810	1770	126.0	271
Hydrogen sulfide	H_2S	34.08	1.409	12.56	1.39	430	42.8	465
Krypton	Kr	83.80	3.429	25.47	3.384	275	55.8	407
Methane	CH_4	16.04	0.657	11.20	0.649	627	56.1	406
n-Butane	C_4H_{10}	58.12	2.491	7.52	2.46	330	18.9	700
n-Pentane	C_5H_{12}	72.15		6.98	2.91	296	16.5	749
n-Hexane	C_6H_{14}	86.17		6.62	3.48	271	14.3	804
Neon	Ne	20.18	0.824	31.57	0.813	559	141.0	256
Nitric oxide	NO	30.01	1.228	19.18	1.21	459	70.3	363
Nitrogen	N_2	28.02	1.146	17.85	1.131	474	67.8	370
Nitrous oxide	N_2O	44.02		14.87	1.78	379	45.0	454
Oxygen	O_2	32.00	1.310	20.51	1.293	444	72.7	357
Propane	C_3H_8	44.09	1.854	8.20	1.83	378	24.1	619
Sulfur dioxide	SO_2	64.07	2.679	12.95	2.64	314	31.8	540
Water	H_2O	18.02		9.05	0.727	592	42.8	465
Xenon	Xe	131.30	5.397	23.21	5.326	219	40.5	478

TABLE 7.6 Leak rate conversion chart.

TO / FROM	Pa m^3/s	Pa L/s	mbar L/s	torr L/s	micron L/s	micron ft^3/s	cm^3/s @ STP[A]	moles/s
Pa m^3/s	1	1.0E3	1.0E1	7.50062	7.50062 E3	2.64882 E2	9.86923	4.40319 E-4
Pa L/s	1.0E-3	1	1.0E-2	7.50062 E-3	7.50062	2.64882 E-1	9.86923 E-3	4.40319 E-7
mbar L/s	1.0E-1	1.0E2	1	7.50062 E-1	7.50062 E2	2.64882 E1	9.86923 E-1	4.40319 E-5
torr L/s	1.33322 E-1	1.33322 E2	1.33322	1	1.0E3	3.53147 E1	1.31579	5.87044 E-5
micron L/s	1.33322 E-4	1.33322 E-1	1.33322 E-3	1.0E-3	1	3.53147 E-2	1.31579 E-3	5.87044 E-8
micron ft^3/s	3.77527 E-3	3.77527	3.77527 E-2	2.83168 E-2	2.83168 E1	1	3.72590 E-2	1.66232 E-6
cm^2/s @ STP	1.01325 E-1	1.01325 E2	1.01325	7.60E-1	7.60E2	2.68391 E1	1	4.46153 E-5
moles/s	2.27108 E3	2.27108 E6	2.27108 E4	1.70345 E4	1.70345 E7	6.01568 E5	2.24138 E4	1

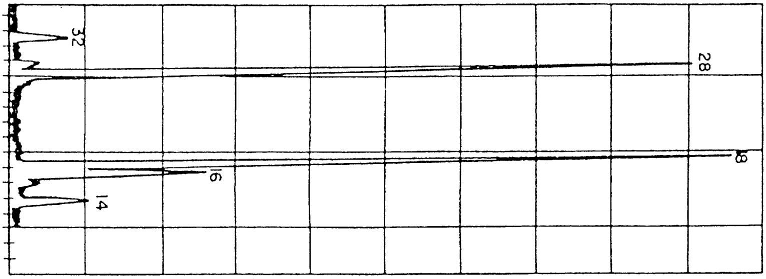
[A] STP is defined as $T = 273.15$ K and $P = 1$ atm.

TABLE 7.7 Pressure units conversion table.

TO FROM	Pascal (Pa) (N/m^2)	torr (mm of Hg)	Standard Atmosphere (atm)	millibar (mbar)	Dyne per Square Centimeter (dyn/cm^2)	cm water (4°C)	micron	psi
Pascal (Pa) (N/m^2)	1	7.5006E-03	9.8692E-06	0.01	10	1.0197E-02	7.5006	1.4504E-04
torr (mm of Hg)	133.3224	1	1.3158E-03	1.3332	1.3332E03	1.3595	1.0E03	1.9337E-02
Standard atmosphere (atm)	1.0132E5	7.60E02	1	1.0132E03	1.0132E06	1.0332E03	7.60E05	1.4696E01
millibar (mbar)	1.0E02	7.501E-1	9.8692E-04	1	1.0E03	1.0197	7.501E02	1.4504E-02
dyne per square centimeter (dyn/cm^2)	1.0E-01	7.501E-04	9.8692E-07	1.0E-03	1	1.0197E-03	7.501E-1	1.4504E-05
cm water (4°C)	9.8064E01	7.3554E-01	9.6781E-04	9.8064E-01	9.8064E02	1	7.3552E02	1.4223E-02
micron	1.3332E-01	1.0E-03	1.3158E-06	1.3332E-03	1.3332	1.3595E-03	1	1.9337E-05
psi	6.8947E03	5.1715E01	6.8046E-02	6.8947E01	6.8947E04	7.0309E01	5.1715E04	1

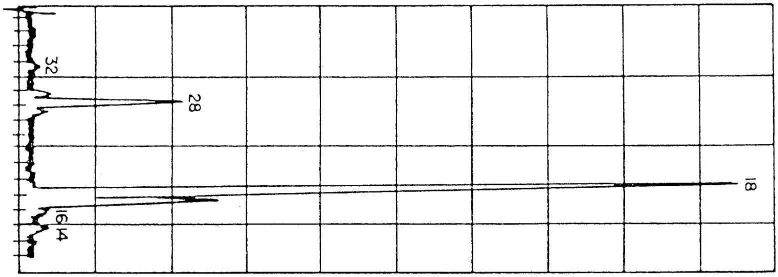
(a)

AIR LEAK
TOTAL PRESSURE – 1.3 x 10^{-6} torr



(b)

VACUUM SYSTEM BACKGROUND
TOTAL PRESSURE – 8.5 x 10^{-7} torr



(c)

NITROGEN LEAK
TOTAL PRESSURE – 1.3 x 10^{-6} torr

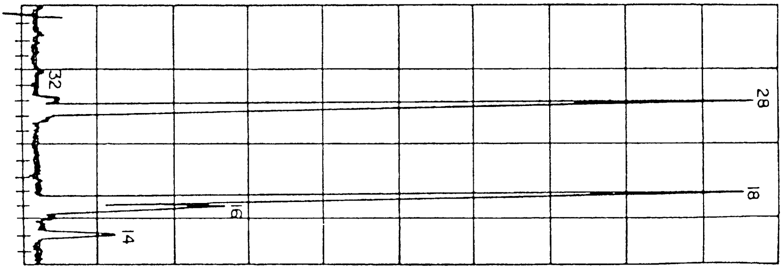


FIG. 7.9 Typical mass spectra for different leak effects. Horizontal axes for all graphs is the mass to charge ratio (*m*/*e*).

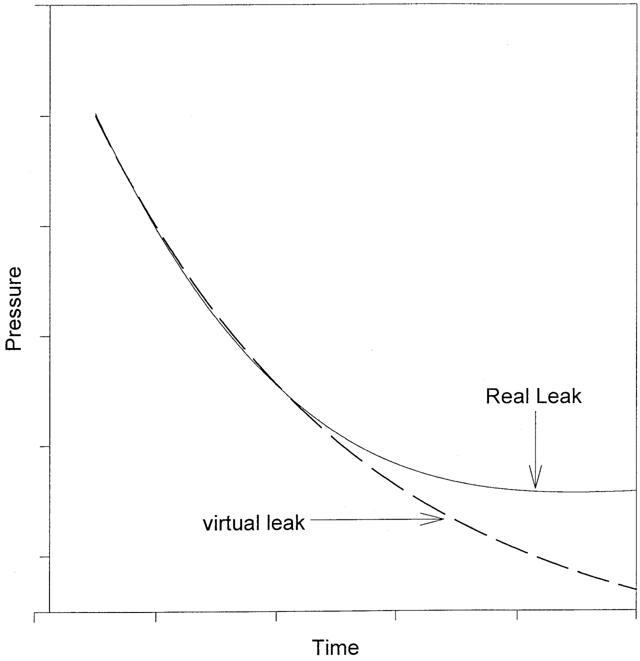


FIG. 7.10 Typical pumpdown curves for vacuum systems with real and virtual leaks. Systems having real leaks reach a stable pressure over time, while systems with virtual leaks never reach stasis.

TABLE 7.8 Sensitivity limits of various methods of leak location.
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Method	Minimum Detectable Leakage Rate, Pa m^3/s	Comments
Mass loss (pressure change)	Time limited	Generally limited to sizable leaks. Gives good overall quantitative measure. No information on leak location. Time consuming.
Ultrasonics	0.05	Leak location only. Fast. No clean up. Can detect from distance. Useful only for fairly large leaks.
Chemical penetrants	10^{-4}; perhaps smaller	Simple to use. Location only. May plug small leaks. Requires clean up.
Bubbles	10^{-5}	For leak location. Fluids may plug small leaks. Requires clean up.
Thermal conductivity	10^{-6}	Simple, compact, portable, inexpensive. Sensitive to a number of different gases. Operates in air.
Halogen	10^{-10}	Operates in air. Sensitive (10^{-12} claimed with SF_6). Portable. Requires clean up. Loses sensitivity with use. Sensitive to ambient halide gases.
Mass spectrometer	10^{-12}	Most accurate for vacuum testing. Expensive. Relatively complex. Not as portable as halogen detectors. Much less sensitive when used in pressure testing.

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3. Ehrlich, C. D. and Basford, J. A., "Recommended Practices for the Calibration and Use of Leaks," *J. Vac. Sci. Technol. A,* Vol. 10, No. 1, January / February 1992.
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5. Abbott, P. J. and Tison, S. A., "Commercial Helium Permeation Leak Standards: Their Properties and Reliability," *J. Vac. Sci. Technol. A,* Vol. 14, No. 3, May / June 1996.

Notes:

Appendix

Selected ASTM Standards for Nondestructive Testing

Ultrasonic Testing

A 388	Standard Practice for Ultrasonic Examination of Heavy Steel Forgings
A 418	Standard Test Method for Ultrasonic Examination of Turbine and Generator Steel Rotor Forgings
A 609	Standard Practice for Castings, Carbon, Low-Alloy, and Martensitic Stainless Steel, Ultrasonic Examination Thereof
A 745	Standard Practice for Ultrasonic Examination of Austenitic Steel Forgings
A 939	Standard Test Method for Ultrasonic Examination from Bored Surfaces of Cylindrical Forgings
B 548	Standard Test Method for Ultrasonic Inspection of Aluminum-Alloy Plate for Pressure Vessels
B 594	Standard Practice for Ultrasonic Inspection of Aluminum-Alloy Wrought Products for Aerospace Applications
B 773	Standard Guide for Ultrasonic C-Scan Bond Evaluation of Brazed or Welded Electrical Contact Assemblies
E 114	Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Examination by the Contact Method

E 164	Standard Practice for Ultrasonic Contact Examination of Weldments
E 214	Standard Practice for Immersed Ultrasonic Examination by the Reflection Method Using Pulsed Longitudinal Waves
E 273	Standard Practice for Ultrasonic Examination of Longitudinal Welded Pipe and Tubing
E 587	Standard Practice for Ultrasonic Angle-Beam Examination by the Contact Method
E 588	Standard Practice for Detection of Large Inclusions in Bearing Quality Steel by the Ultrasonic Method
E 1001	Standard Practice for Detection and Evaluation of Discontinuities by the Immersed Pulse-Echo Ultrasonic Method Using Longitudinal Waves
E 1315	Standard Practice for Ultrasonic Examination of Steel with Convex Cylindrically Curved Entry Surfaces
E 1685	Standard Practice for Measuring the Change in Length of Fasteners Using the Ultrasonic Pulse-Echo Technique
E 1816	Standard Practice for Ultrasonic Examinations Using Electromagnetic Acoustic Transducer (EMAT) Techniques
E 1961	Standard Practice for Mechanized Ultrasonic Examination of Girth Welds Using Zonal Discrimination with Focused Search Units
E 1962	Standard Test Method for Ultrasonic Surface Examinations Using Electromagnetic Acoustic Transducer (EMAT) Techniques
F 1512	Standard Practice for Ultrasonic C-Scan Bond Evaluation of Sputtering Target-Backing Plate Assemblies

Radiography

E 94	Standard Guide for Radiographic Testing
E 1030	Standard Test Method for Radiographic Examination of Metallic Castings
E 1032	Standard Test Method for Radiographic Examination of Weldments
E 1742	Standard Practice for Radiographic Examination

F 629	Standard Practice for Radiography of Cast Metallic Surgical Implants

Electromagnetic Testing

E 243	Standard Practice for Electromagnetic (Eddy-Current) Examination of Copper and Copper-Alloy Tubes
E 309	Standard Practice for Eddy-Current Examination of Steel Tubular Products Using Magnetic Saturation
E 426	Standard Practice for Electromagnetic (Eddy-Current) Examination of Seamless and Welded Tubular Products, Austenitic Stainless Steel and Similar Alloys
E 570	Standard Practice for Flux Leakage Examination of Ferromagnetic Steel Tubular Products
E 571	Standard Practice for Electromagnetic (Eddy-Current) Examination of Nickel and Nickel Alloy Tubular Products
E 690	Standard Practice for In Situ Electromagnetic (Eddy-Current) Examination of Nonmagnetic Heat Exchanger Tubes
E 1033	Standard Practice for Electromagnetic (Eddy-Current) Examination of Type F-Continuously Welded (CW) Ferromagnetic Pipe and Tubing Above the Curie Temperature
E 1312	Standard Practice for Electromagnetic (Eddy-Current) Examination of Ferromagnetic Cylindrical Bar Product Above the Curie Temperature
E 1571	Standard Practice for Electromagnetic Examination of Ferromagnetic Steel Wire Rope
E 1606	Standard Practice for Electromagnetic (Eddy-Current) Examination of Copper Redraw Rod for Electrical Purposes

Penetrant Testing

E 165	Standard Test Method for Liquid Penetrant Examination
E 1208	Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Lipophilic Post-Emulsification Process

E 1209	Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Water-Washable Process
E 1210	Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Hydrophilic Post-Emulsification Process
E 1219	Standard Test Method for Fluorescent Liquid Penetrant Examination Using the Solvent-Removable Process
E 1220	Standard Test Method for Visible Liquid Penetrant Examination Using the Solvent-Removable Process
E 1417	Standard Practice for Liquid Penetrant Examination
E 1418	Standard Test Method for Visible Penetrant Examination Using the Water-Washable Process
F 601	Standard Practice for Fluorescent Penetrant Inspection of Metallic Surgical Implants

Magnetic Particle Testing

A 275	Standard Test Method for Magnetic Particle Examination of Steel Forgings
A 456	Standard Specification for Magnetic Particle Examination of Large Crankshaft Forgings
A 966	Standard Test Method for Magnetic Particle Examination of Steel Forgings Using Alternating Current
A 986	Standard Specification for Magnetic Particle Examination of Continuous Grain Flow Crankshaft Forgings
E 709	Standard Guide for Magnetic Particle Examination
E 1444	Standard Practice for Magnetic Particle Examination

Leak Testing

E 427	Standard Practice for Testing for Leaks Using the Halogen Leak Detector (Alkali-Ion Diode)
E 493	Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Inside-Out Testing Mode
E 498	Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Tracer Probe Mode
E 499	Standard Test Methods for Leaks Using the Mass Spectrometer Leak Detector in the Detector Probe Mode

E 515	Standard Test Method for Leaks Using Bubble Emission Techniques
E 1002	Standard Test Method for Leaks Using Ultrasonics
E 1003	Standard Test Method for Hydrostatic Leak Testing
E 1066	Standard Test Method for Ammonia Colorimetric Leak Testing
E 1603	Standard Test Methods for Leakage Measurement Using the Mass Spectrometer Leak Detector or Residual Gas Analyzer in the Hood Mode
E 2024	Standard Test Methods for Atmospheric Leaks Using a Thermal Conductivity Leak Detector

Subject Index

About the Editor

LEONARD MORDFIN earned a bachelor's degree from The Cooper Union, and master's and Ph.D. degrees from the University of Maryland, all in mechanical engineering. He has been an independent consultant in both mechanical testing and nondestructive testing since 1994. Prior to that, he spent most of his career at the National Institute of Standards and Technology (formerly the National Bureau of Standards) where his principal activities included research on stability, creep, fatigue, and fracture of aircraft structures, and the development of standards for nondestructive testing. He also held management positions as deputy and acting chief of the Office of Nondestructive Evaluation and leader of the Mechanical Properties & Performance Group in the Metallurgy Division. Dr. Mordfin also served a two-year assignment as program manager for materials research at the Air Force Office of Aerospace Research.

He has more than 60 publications to his name, including book and encyclopedia chapters as well as journal papers. He has edited 5 books, among them *Mechanical Relaxation of Residual Stresses* and, with Harold Berger, *Nondestructive Testing Standards: Present and Future*. He has lectured extensively in the United States as well as in Australia, Canada, Israel, Japan, Norway, Singapore, and South Korea.

Dr. Mordfin is the recipient of numerous awards for his work, including the ASTM Award of Merit for his service to Committee E28 on Mechanical Testing, the Charles W. Briggs Award from ASTM Committee E07 on Nondestructive Testing, the Edward Bennett Rosa Award from NIST, a Bronze Medal from the U.S. Department of Commerce, and a Superior Performance Award from the Department of the Air Force.

A past chairman of ASTM's Committee on Publications, Dr. Mordfin presently serves the Society as chairman of its subcommittees on residual stress measurement and mechanical testing terminology, and its section on infrared methods of nondestructive testing. He is the principal U.S. delegate to the ISO technical committee on nondestructive testing, and chairman of the USA Technical Advisory Group for that ISO committee. He is also a member of the USA Technical Advisory Group for the ISO technical committee on mechanical testing.

A fellow of ASTM, Dr. Mordfin is also a longtime member of the American Society for Nondestructive Testing and the Society for Experimental Mechanics.

ISBN 0-8031-2092-3