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COMPENDIUM OF SHOCK WAVE DATA

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Notice

The completeness of this compilation depends upon its users. To assure its continued usefulness, users are urged to send any missing or new shock wave data and corrections to the Editor, M. van Thiel, Lawrence Livermore Laboratory, P.O. Box 808, Livermore, California, U.S.A., 94550.

New and revised pages will be distributed as necessary.

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COMPENDIUM OF SHOCK WAVE DATA

Introduction

Abstract

The purpose of this volume is to list in a concise manner the thermodynamic data in condensed media obtained by shock wave techniques. The volume should be useful both to people working in the shock wave field and to others interested primarily in thermodynamic properties at high pressure. Therefore, both dynamic variables and volumetric quantities associated with the shock wave are given. The format has been selected to make the volume useful in engineering as well as scientific research activities.

Content

Tabular Data — The information tabulated is generally derived from shock compression of a sample of known density. Any two of the measurable quantities tabulated (pressure, volume or density, free-surface and particle velocity behind the shock front, as well as shock velocity) may be used to derive the others. Shock and free-surface velocities were measured in most of the experiments performed to date. A description of the basic assumptions and techniques has been given by Rice et al.[1] Some useful texts also exist for those interested in the experimental techniques[2] and for those more theoretically inclined.[2-4]

Pressure (P), volume (V), and energy (E) are usually obtained from the shock (U_s) and particle velocity (U_p) by application of the conservation conditions of mass momentum and energy across a well-defined shock wave. It is, therefore, assumed that steady state exists in front and behind this wave. The conditions are schematically presented in Fig. 1. The distance between the two (cross-hatched) steady-state regions is usually small compared to the dimensions of the system. Conservation of mass and momentum then yields:

$$P_1 - P_0 = \left(U_{s_1} - U_{p_0}\right)\left(U_{p_1} - U_{p_0}\right)/V_0$$

and

$$V_1/V_0 = 1 - \frac{U_{p_1} - U_{p_0}}{U_{s_1} - U_{p_0}} ,$$

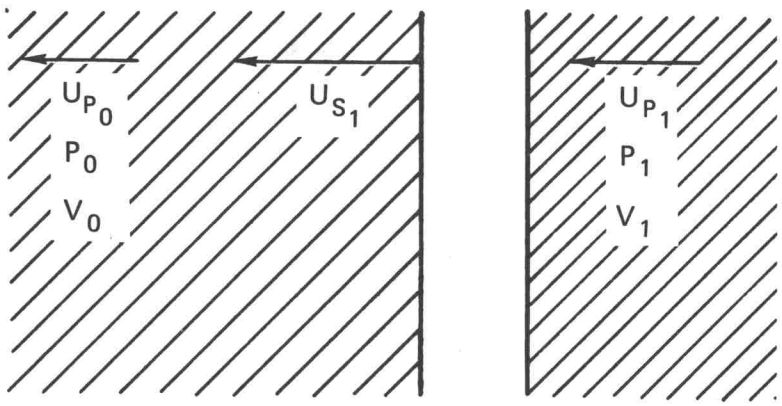


Fig. 1. Shock wave conditions.

while the energy conservation condition is:

$$E_1 - E_0 = (1/2)\ (P_0 + P_1)\ (V_0 - V_1).$$

In the usual single wave experiment, the initial particle velocity, U_{P_0}, is zero. Frequently multiple waves are considered in this compilation. The more general form of the above equations for multiple wave systems is obtained by replacing the subscript 0 by i and 1 by i + 1.

Whenever they are obtainable from shock wave measurements, other directly measured derivatives, such as heat capacity and expansion coefficient, are also listed. However, there is no developed technology for these measurements at the time of this writing.

A convenient summary of the tabulated data may be given in terms of a functional relation between shock (U_s) and particle velocity (U_p) since a valuable feature of dynamic (shock wave) measurements is the slow, and in many cases, vanishing curvature of plots of U_s vs U_p. Least-square fits have been given in this plane whenever the data warrant it:

$$U_s = C + \sum_{i=1}^{n} S_i\ U_p^i\ .$$

The sum is limited to $n_{max} = 1$ for most solids. This Hugoniot equation may be transformed to the pressure-volume plane by use of conservation of mass and momentum equations.

With each set of data from a particular source, the properties that define the initial condition of the sample before shock compression are listed if available. These are:

- V_0: Initial volume.
- V_{0i}: Volume from crystallographic or accurate volumetric techniques (useful for porous materials).
- T_0: Initial temperature.
- Composition.
- C_ℓ, C_s, and C_b or C_0: Respective longitudinal sound velocity, transverse (or shear) wave velocity, and "bulk sound velocity" [$\equiv(\partial P/\partial\rho)_S^{1/2}$ km/sec] derived from static compression or for an isotropic sample $(C_L^2 - 4/3\ C_s^2)^{1/2}$.

The quantity C_0 is helpful in allowing interpolations of the bulk compressibility between the lower limit of the dynamic range and the compressibility at one atmosphere.

It may be noted that no subscripts have been printed in the body of the compendium. This is due to the limited character list of the automatic printer that produced these pages. Therefore, V_0 is written as V0, C_ℓ' as CL, etc.

While the above characterization is adequate for most purposes, some structural transformations are comparable to or slower than the measuring time in shock experiments. Under these conditions, other sample specifications are needed to adequately describe the sample. This problem has come up in detailed investigations of dynamic yield points and in the study of phase transitions and chemical reactions. In the former case, for example, impurity concentration and thermal history become highly important. Mixtures of solids and liquids exhibit relaxation times that depend in a complex fashion on microscopic structure and strength and, for high pressure shocks, on the temperature distribution behind the front.

Comments — A comments section is provided for further characterizations of the material and the experiment. The first comment is reserved for a source statement. This may be the name of a person and an address or journal reference. The second comment contains a characterization of the experimental method and the technique of data analysis. To avoid lengthy descriptions on each data page, short descriptions of each method are given in the section on techniques. These descriptions, of course, do not dwell on details of experimental setup or data handling but are primarily an attempt to give a short and unambiguous classification of a series of data recording and analysis methods. For more detail, the user is referred to papers and books on the subject. A review has been given by Duval and Fowles.[2]

Any number of comments may be listed by the compiler or suggested by the investigator. The extent and format of these comments are flexible and depend on relatively arbitrary decisions of the compiler. It is clear that these comments can never replace the full publication.

Filing Order

The filing order chosen for this volume is independent of arbitrary nomenclature and trade names and, when understood, is equally useful to any language group. However, for those users preferring the English language as a basis for searching this volume, an index for each section is provided. The author index for each section is a convenient guide to the contributors.

The filing order is based on the periodic table. The basic system is described in detail by the Office of Critical Tables,[5] and some modifications have been made in accordance with the latest modification of a numerical order of the elements proposed by Rossini.[6] (See Table 1 and Fig. 4 at the end of the techniques listings.) With some small exceptions, the categories, too, are essentially those given by Rossini. They are:

A_1. Elements: Filed by order number. For example: O - #1 is filed before H - #2, before He - #3, etc.

A_2. Compounds, including intermetallic compounds: These are divided into groups which are determined by the element in the compound with the largest order number. Subsets within this group are then determined by the element with the next to highest number, etc. To this end, each compound is characterized by the set of order numbers (called index or finding numbers) of its elements written in order of decreasing order number.

For example:

Name	Formula	Index
Sodium oxide	Na_2O*	99-1
Sodium hydroxide	NaOH	99-2-1
Sodium fluoride	NaF	99-9
Sodium chloride	NaCl	99-10
Sodium sulfate	Na_2SO_4	99-14-1
Sodium carbonate	Na_2CO_3	99-23-1

*Note that the automatic printer used for the data pages is restricted to capital letters, so that the molecular formulas must be written with their elements separated by dashes or brackets: Na_2O becomes NA2-O, etc.

These are all members of the group filed under sodium in the above order. All potassium compounds (#100) containing elements with numbers not larger than 100 follow this group, while all lithium compounds containing elements with numbers not larger than 98 precede the sodium group, etc.

The only compounds excluded from this category are those with two or more carbon atoms (#23) and no elements above #23. These are filed separately under categories B and C.

B. Hydrocarbons: Organic compounds containing only C (#23) and H (#2).

For example:

Name	Formula	Index
Methane	CH_4	23-2 (1-4)
Benzene	C_6H_6	23-2 (6-6)
Hexane	C_6H_8	23-2 (6-8)
Octane	C_8H_{10}	23-2 (6-10)

are listed in the above order. Therefore, in order to find a hydrocarbon, one must first find the set containing the correct number of carbon atoms and, second, the compound with the proper number of hydrogen atoms of that set. Polymers are filed under the monomer.

C. All other organic compounds: Compounds with more than two carbon atoms (#23) and no element with order number larger than 23.

D. Alloys, solutions, and mixtures: Materials that are not simple compounds and that contain no component (element or compound) over 90 mole percent. Those that contain a component over 90 mole percent will be listed under A_1, A_2, B, or C to avoid scattering almost pure materials under different headings.

The finding number may be a compound number derived from the constituent compounds. The leading index will be that of the major constituent — not necessarily the one containing the largest order number.

For example:

41-24-1--93-24-1

Olivine

(Name)	(Formula)	(Composition)
Fayalite	Fe_2SiO_4	55.0%
Forsterite	Mg_2SiO_4	45.0%

In this case, the compound index consists of the indexes of two minerals (Fayalite and Forsterite). These indexes are of necessity complex, but they allow for a minimum amount of conflict in filing order. No distinction has, so far, been made between solutions and granular mixtures in generating the index numbers.

The above example forms the heading for the data page of the particular rock.

A large number of the materials studied have not been characterized sufficiently to allow assignment of a finding number. These materials are, however, useful for many engineering applications. They are synthetic composites and geological materials and are generally categorized as mixtures or organic plastics. A separate section has been provided for these materials at the end of this compendium.

Techniques

Experimental:

A. Pin: The surface accelerated by the shock wave under study may be used as one pole of a switch. The value and complexity of this technique for locating shock and free-surface position as a function of time are well illustrated by the experiments on iron of Bancroft et al.[7] In these experiments, the switch completes a current path and causes a capacitor to discharge. Alternatively, a voltage or current pulse may be produced by a ferroelectric or piezoelectric crystal on impact with a surface. A description of some pin types has been given by van Thiel and Alder.[8]

B. Optical flash: The moving surface may be used to compress a thin layer (0.01-0.1 mm) of argon or xenon gas. This shock compression results in a flash which is then recorded by a smear camera. This technique has been adequately described by Rice et al.[1] and by McQueen et al.[9]

C_1. Reflectivity change of a mirror: An optically reflecting surface will turn opaque when impacted with sufficient strength by a shocked material. A smear camera is focused on a mirror placed on the surface to be shocked or some distance from it and records arrival of the shock wave or the free surface, respectively.[2]

C_2. Turning mirror: Frequently surface structure of shock strength is such that the surface of the mirror does not change reflectivity rapidly enough. In this case, the mirror may be placed at an angle to the shock front or surface. Impact then causes the mirror to turn through an angle, thus removing a parallel beam of light from the optical path. This technique is more reliable for smooth surfaces than technique C_1 but requires more care in the optical setup.[2]

C_3. Total reflection of a prism[10]: This is a variation of the mirror technique. Closing a void (as small as a micron) between a sample and a glass or other transparent prism will change the angle of total internal reflection. A beam of light reflected internally close to the critical angle will, therefore, be rapidly cut off when the void is closed. The prism may be placed either on the surface or at some angle to it to determine either the arrival time of the shock or the velocity of the surface.

D. "Optical lever": The optical-lever technique employs the change of position of an optical image in a reflecting surface when this surface is turned by a shock wave. In this case, the shock front makes a known finite angle with the surface. The measurement of the displacement of a series of images made by different parts of the surface and the observation of the time of displacement of these images yields the required shock and free-surface parameters.[2]

E. "Knife edge": The knife-edge or moving-image technique yields higher spatial resolution than the optical-lever technique. Here a thin wire or knife edge is suspended over the polished surface of the specimen. The separation of the knife edge and its image may be photographed as a function of time to yield the surface velocity. This technique was first reported by Davis and Craig.[11]

F. Resistance wire: This technique, first described in a Sandia Laboratories report,[12] has been used to measure free-surface velocity. Here a change of resistance is measured as the moving surface shorts out a resistance wire positioned at an angle to the surface. The velocity of the free surface is then obtained from the resistance-time record. Shock velocity may be obtained if the wire is parallel to the surface and the shock direction is other than normal.

G. Capacitor: The capacitor technique measures the change of capacitance of a parallel plate capacitor, one plate of which is the surface whose velocity is to be measured.[13]

H. Polarization: The polarization technique[14] uses the shape of an electrical pulse produced by the shock to measure shock velocity in cases where the shock wave changes the dielectric polarization of the sample.

I. Transducer: While the above techniques measure shock or surface motion, several transducer techniques that give pressure directly have been developed or are under development. In these cases, a measured voltage change is related to pressure by calibration against one of the primary techniques mentioned above. Some examples are:

- Conductivity gauge: The sulfur gauge was first developed by Eichelberger and Hauver.[15] It is based on the change of conductivity of a sulfur wafer with pressure. Another useful material for pressure measurement is manganin wire, used previously in static work because of its linear pressure versus resistivity curve. Some work has been done to extend this curve to higher pressures.[16]
- Piezoelectric gauge: The quartz gauge[17] and the lithium niobate gauge,[18] which are based on the piezoelectric coefficient, yield useful pressure measurements up to about 50 kbar and 15 kbar, respectively. A calibration curve may be obtained from R. A. Graham, Sandia Laboratories, Albuquerque. Tourmaline has been used and a calibration up to 21 kbar[19] has been reported.

J. Radiographic methods: These may measure either one of two sets of parameters.

- The shock velocity and density change across the shock front. This method has been described by Schall.[20]
- The shock velocity and the velocity of an embedded foil of higher specific absorption index. This method is valuable in that it yields P, V, and E points independently of a model or a standard material. Its limitations lie in the relatively poor shock front resolution.

K. Magnetic induction: This may be used in interface and free-surface velocity measurements.

- A current loop made of foil or flattened wire may be embedded in a nonconducting sample or placed at an interface.[21,22] The voltage induced in the wire when the wire is moved through an externally applied uniform magnetic field is a measure of material velocity.
- Similarly, a voltage may be induced in a current loop placed concentric to a magnetic pole and close to a moving surface.[23] This method is relatively inexpensive and may be used to measure the motion of any metallic-nonmetallic interface.

Data Reduction:

The parameters obtained from most experimental techniques used to date are shock velocity (U_s) and surface velocity (U_{fs}). The surface velocity may be either the velocity of a projectile generating pressure in the sample (Fig. 2) or the velocity of the sample surface after the shock has traveled through the sample. The pressure change $P - P_0 = \rho_0 U_s U_p$ is a function of shock velocity and the change of mass velocity across the front. Techniques for calculating this latter velocity are discussed below.

A. If the projectile and the sample (Fig. 2(a)) are made of the same material, the shock velocity in the sample and in the projectile (relative to the unshocked medium in front of the wave) is the same. Therefore, the dynamic impedance $\rho_0 U_s = P/U_p$, $\tan\theta_1 = \tan\theta_2$, where from symmetry (Fig. 2(b)) U_p is equal to one-half the projectile velocity before impact and equal to the change of mass velocity across the wave. If the projectile and the sample are not the same, the projectile Hugoniot (H_2) is used as a known standard (Fig. 2(c)).

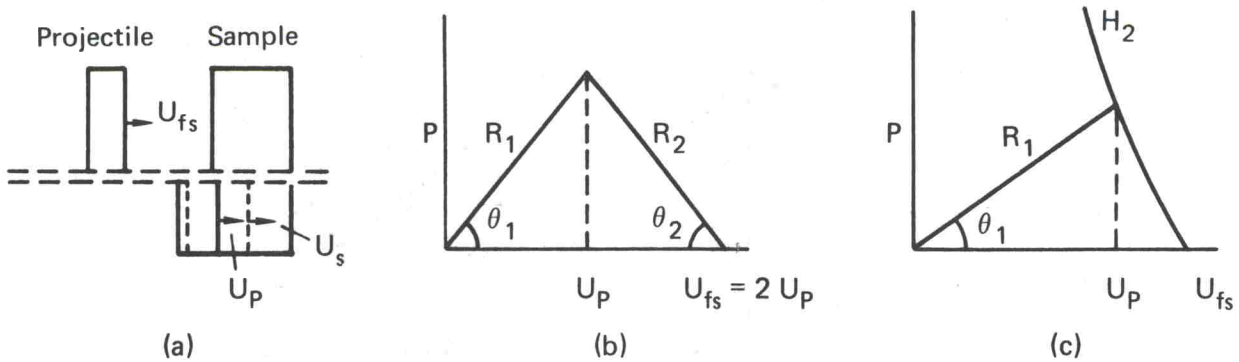


Fig. 2. Velocity diagrams.

The solution is then given by the intersection of R_1 and H_2. The equations to be solved are therefore:

In Fig. 2(b):

$$(P - P_0)_{sample} = (\rho_0 U_s) \tag{1a}$$

and

$$(P - P_0)_{projectile} = (\rho_0 U_s)(U_{fs} - U_p). \tag{1b}$$

Or in Fig. 2(c):

$$(P - P_0)_{sample} = (\rho_0 U_s) U_p, \tag{1c}$$

and the equation of the projectile Hugoniot

$$(P - P_0)_{projectile} = f(U_{fs} - U_p). \tag{2}$$

B_1. Where the velocity of a projectile is not measured, the sample is positioned on a plate (the standard) with a known Hugoniot locus (H) and unloading isentropes (a). As is shown in Fig. 3, the solution is given by the dynamic impendance condition of the sample

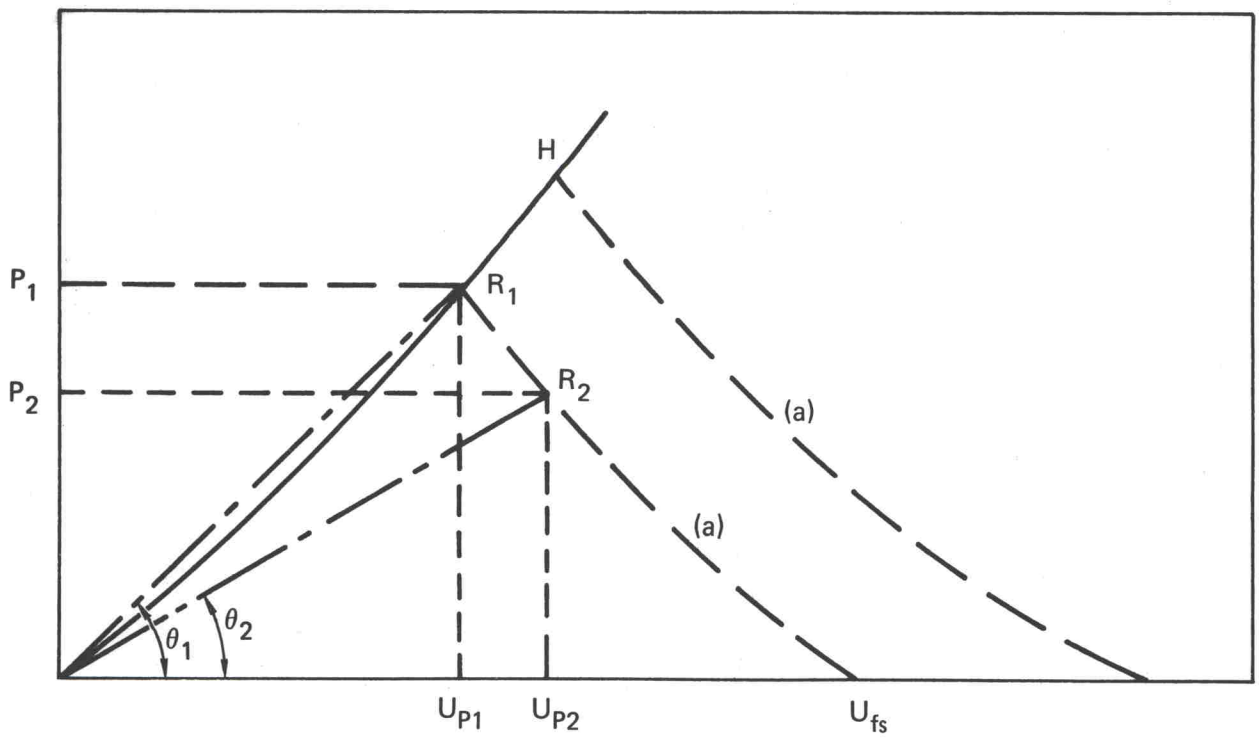


Fig. 3. Projectile velocity.

($\tan\theta_1 = \rho_0 U_s$), and the particular unloading path (a) that crosses the Hugoniot point of the plate at the experimental pressure (P_1). The latter is selected on the basis of a measurement of U_{fs} or $\rho_0 U_s = \tan\theta_1$ of the plate. The solution of P_1 and U_{p1} is, therefore, obtained from:

$$P_2 - P_0 = \Delta P \text{ (sample)} = (\tan\theta_2)\, U_{p2} \tag{1d}$$

and the equation of the unloading adiabat

$$\begin{aligned} P_2 = P_a \text{ (plate)} &= f_a\,(U_s,\ U_{fs} - U_{p2}) \\ &= f'_a\,(U_{fs},\ U_{fs} - U_{p2}). \end{aligned} \tag{3}$$

B_2. A modification of technique B_1 places the material with known equation of state on the sample. The measured quantities are usually the shock and (or) free-surface velocity of the known standard and the shock velocity of the unknown. Consider P_2 as the known pressure and P_1 as the pressure to be determined (Fig. 3). Since the cross curve (a) is not known in this case, the acoustic approximation angle

$$P_2R_2R_1 \simeq \theta_1 = \rho_1 U_{s_1} \tag{4}$$

may be made to yield a first-order solution

$$P_1/P_2 = (\theta_1 + \theta_2)/2\theta_2. \tag{5}$$

After several points are thus obtained, the solution may be improved by iteration. When the shock front is not parallel to the sample-standard interface, appropriate components must be used.[24]

C. Where the pressure is measured directly with a transducer, the other parameter usually measured is the shock velocity through the sample. The conservation of mass and momentum conditions mentioned before may be rearranged to give

$$V/V_0 = 1 - \frac{U_P}{U_s} = 1 - \frac{P - P_0}{\rho_0 U_s^2}\ . \tag{6}$$

Once P and V are known, conservation of energy then yields the energy change

$$E - E_0 = 1/2\ (P_0 + P)\ (V_0 - V)\ . \tag{7}$$

D. If only U_s and U_{fs} are available from a set of experiments, a Hugoniot may be obtained with:

- The assumption that $U_p = 1/2\ U_{fs}$. This is a good approximation at sufficiently low shock compression.
- Otherwise, a model of the thermal expansion or thermal pressure coefficient is used to calculate adiabats from an assumed Hugoniot. A first-order estimate may be the first assumption above.

The Rieman integral

$$U_r = \int_{V_0}^{V} \sqrt{\left|\frac{\partial P}{\partial V}\right|}\, dV$$

along an isentrope is then assumed to yield the increase in mass velocity when shocked material, initially at some pressure P_1 and particle velocity U_p (Fig. 3), unloads to P_0 and $U_{fs} = U_p + U_r$. These techniques have been discussed in detail by Walsh[25] and by Al'tshuler.[26]

This model assumes equilibrium within the state considered. Some uncertainty exists at the time of this writing on how to treat small but measurable effects due to slow relaxation processes behind or in a shock wave. These may be important near-phase transitions or in the pressure range of elastic yield.

E. Where a radiographic method has given U_s and V/V_0, U_p is obtained directly from Eq. (6) and P from the pressure equation given on page 1.

F. The before-mentioned conservation conditions may be applied without rearranging where U_s and U_p are given directly.

G. If a transducer with a known Hugoniot equation ($U_s = F(P)$, $U_p = F(P)$) like quartz is impacted onto the sample or is impacted by the unknown, all required quantities can be calculated from a measure of P and impact velocity, since P(tr) = P(sa), and $U_p(sa) = U - U_p(tr)$, where tr is the transducer, sa is the sample and U is the impact velocity.

Table 1. Order of the elements.

Actinium	Ac	91	Indium	In	31
Aluminum	Al	29	Iodine	I	12
Americium	Am	85	Iridium	Ir	46
Antimony (Stibium)	Sb	21	Iron	Fe	41
Argon	Ar	5	Krypton	Kr	6
Arsenic	As	20	Lanthanum	La	76
Astatine	At	13	Lead	Pb	27
Barium	Ba	96	Lithium	Li	98
Berkelium	Bk	83	Lutetium	Lu	62
Beryllium	Be	92	Lawrencium	Lw	77
Bismuth	Bi	22	Magnesium	Mg	93
Boron	B	28	Manganese	Mn	48
Bromine	Br	11	Mendelevium	Mv	79
Cadmium	Cd	34	Mercury (Hydrargyrum)	Hg	35
Calcium	Ca	94	Molybdenum	Mo	52
Californium	Cf	82	Neodymium	Nd	73
Carbon	C	23	Neon	Ne	4
Cerium	Ce	75	Neptunium	Np	87
Cesium	Cs	102	Nickel	Ni	39
Chlorine	Cl	10	Niobium (Columbium)	Nb	55
Chromium	Cr	51	Nitrogen	N	18
Cobalt	Co	40	Nobelium	No	78
Copper	Cu	36	Osmium	Os	47
Curium	Cm	84	Oxygen	O	1
Dysprosium	Dy	67	Palladium	Pd	42
Einsteinium	D	81	Phosphorus	P	19
Erbium	Er	65	Platinum	Pt	45
Europium	Eu	70	Plutonium	Pu	86
Fermium	Fm	80	Polonium	Po	17
Fluorine	F	9	Potassium (Kalium)	K	74
Francium	Fr	103	Promethium	Pm	72
Gadolinium	Gd	69	Protactinium	Pa	89
Gallium	Ga	30	Praseodymium	Pr	74
Germanium	Ge	25	Radium	Ra	97
Gold	Au	38	Radon	Rn	8
Hafnium	Hf	59	Rhenium	Re	50
Helium	He	3	Rhodium	Rh	43
Hydrogen	H	2	Rubidium	Rb	101
Holmium	Ho	66	Ruthenium	Ru	44

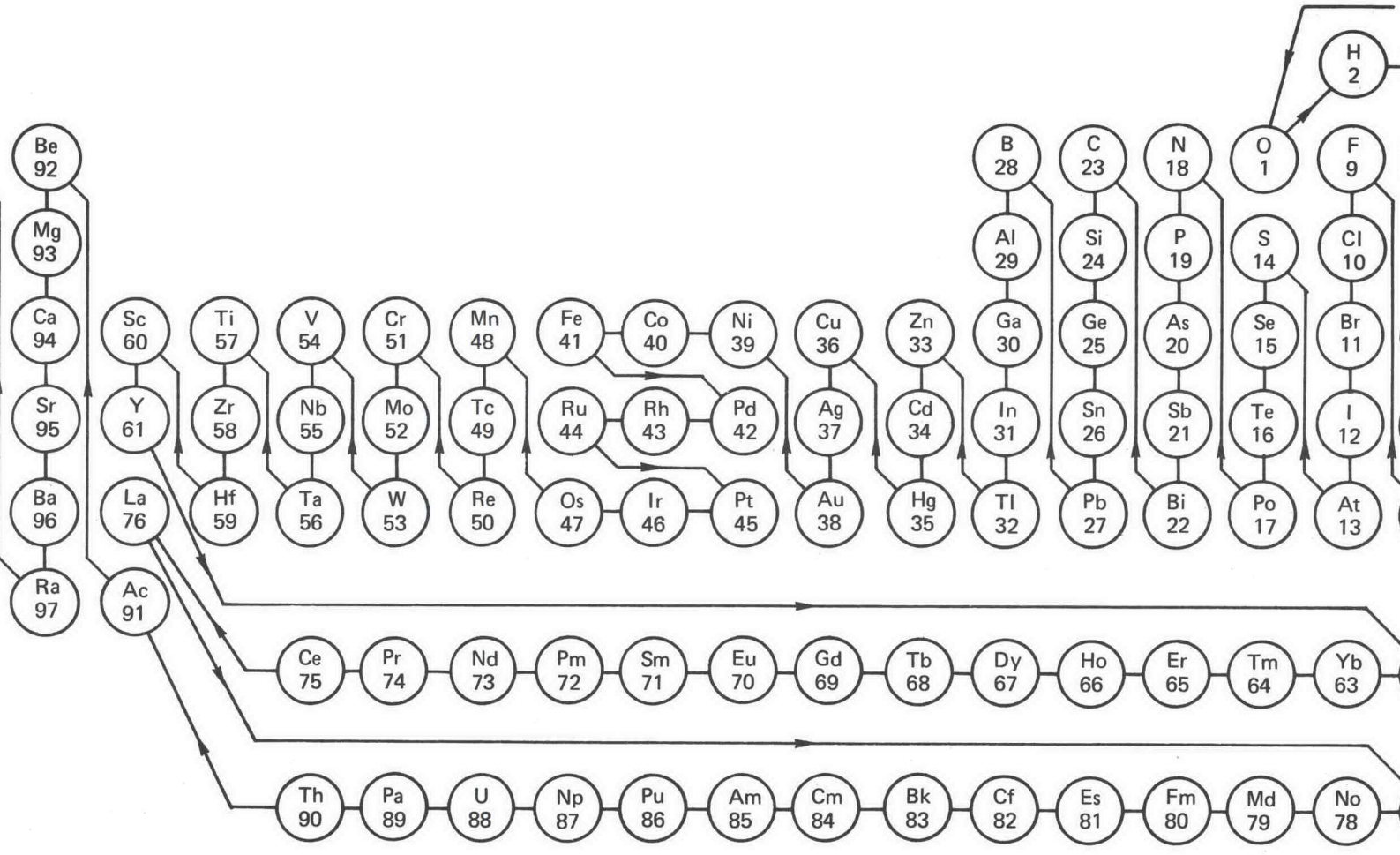


Fig. 4. Standard order of arrangement of the chemical elements.

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