

**NIST Technical Note  
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# **Melting Points and Boiling Points for the Alkali Metals**

Nikhila Narayana  
Donald R. Burgess, Jr.

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## **Abstract**

In this work, we compiled, evaluated, and selected recommended values for the normal melting points ( $T_m$ ) and normal boiling points ( $T_b$ ) of the alkali metals: lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), and francium (Fr). We also compiled and evaluated vapor pressures for lithium and fitted these sets of data in order to both more accurately determine the boiling point and to derive a real gas enthalpy of vaporization (employing a compressibility factor  $Z$ ). For all values reported prior to 1990, we corrected the values to the International Temperature Scale of 1990 (ITS-90).

## **Keywords**

Alkali metal; melting point; boiling point; vapor pressure; enthalpy of vaporization; critical evaluation.

## Table of Contents

<b>1. Introduction</b> .....	<b>1</b>
1.1. Overview .....	1
1.2. Notation Used.....	2
Table 1. Notation Used.....	2
1.3. International Temperature Scale .....	3
1.4. Corrections to the Temperature Scale from IPTS-48 and IPTS-68.....	5
Table 2. Recommended values for the melting points and boiling points of the alkali metals. Expanded uncertainties $U$ ( $2\sigma$ , 95 % coverage), and corrections from IPTS-68 and IPTS-48 to the ITS-90 Temperature Scale ( $T_{90}$ ). .....	5
1.5. Uncertainties .....	6
<b>2. Alkali Metals Melting Points</b> .....	<b>7</b>
2.1. Overview .....	7
Table 3. Recommended values for the melting points of the alkali metals. ....	8
Figure 1. Trend in melting points of the alkali metals. ....	8
2.2. Lithium (Li) Melting Point .....	9
Table 4. Melting Points of Lithium (Li).....	10
Figure 2. Melting point values and recommendation for lithium. The solid point is the recommended value and the dotted lines represent the expanded uncertainty.....	11
2.3. Sodium (Na) Melting Point .....	12
Table 5. Melting Points of Sodium (Na).....	13
Figure 3. Melting point values and recommendation for sodium. The solid point is the recommended value, and the dotted lines represent the expanded uncertainty.....	15
2.4. Potassium (K) Melting Point .....	16
Table 6. Melting Points of Potassium (K).....	17
Figure 4. Melting point values and recommendation for potassium. The solid point is the recommended value, and the dotted lines represent the expanded uncertainty.....	18
2.5. Rubidium (Rb) Melting Point .....	19
Table 7. Melting Points of Rubidium (Rb).....	20
Figure 5. Melting point values and recommendation for rubidium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.....	21
2.6. Cesium (Cs) Melting Points .....	22
Table 8. Melting Points of Cesium (Cs).....	23

Figure 6. Melting point values and recommendation for cesium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.....	24
2.7. Francium (Fr) Melting Point.....	25
Table 9. Melting Points of Francium (Fr) .....	25
<b>3. Alkali Metals Boiling Points.....</b>	<b>26</b>
3.1. Overview .....	26
Table 10. Recommended values for the boiling points of the alkali metals. ....	27
Figure 7. Trend in boiling points of the alkali metals.....	27
3.2. Lithium (Li) Boiling Point.....	28
Table 11. Boiling Points of Lithium (Li) .....	29
Figure 8. Boiling point values from Table 11 and recommendation for lithium from a fit to vapor pressure curves (see later table and figure). The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty. ....	30
3.3. Alkali Metal Vapor Pressures and Enthalpies of Vaporization .....	31
Table 12. Vapor Pressures of Lithium (Li) and Heats of Vaporization (ideal and real gas) ...	32
Figure 9. Deviation of Lithium Vapor Pressures from a Fit to $\ln(P) = a + b/T + c \cdot \ln(T)$ , .....	33
3.4. Sodium (Na) Boiling Point .....	34
Table 13. Boiling Points of Sodium (Na) .....	35
Figure 10. Boiling point values for sodium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty. ....	37
3.5. Potassium (K) Boiling Point.....	38
Table 14. Boiling Points of Potassium (K) .....	39
Figure 11. Boiling point values for potassium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty. ....	41
3.6. Rubidium (Rb) Boiling Point.....	42
Table 15. Boiling Points of Rubidium (Rb) .....	42
Figure 12. Boiling point values for rubidium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty. ....	44
3.7. Cesium (Cs) Boiling Point .....	45
Table 15. Boiling Points of Cesium (Cs).....	46
Figure 13. Boiling point values for cesium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty. ....	48
3.8. Francium (Fr) Boiling Point .....	49
Table 13. Boiling Points of Francium (Fr).....	49

<b>4. Summary .....</b>	<b>50</b>
<b>Declaration of Competing Interest.....</b>	<b>51</b>
<b>Data Availability .....</b>	<b>51</b>
<b>Acknowledgements .....</b>	<b>51</b>
<b>5. References .....</b>	<b>52</b>

## **1. Introduction**

### **1.1. Overview**

In this work, we compiled, evaluated, and selected recommended values for use for the normal melting points and normal boiling points of the alkali metals: lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), and francium (Fr). Normal melting and boiling points are defined as the transition temperatures at 1 atm (101.325 kPa). Throughout this paper, when we use the phrases, “melting point” or “boiling point,” we are referring to normal melting or boiling points. There are many values contained in various handbooks and compilations. These sources, however, often do not provide uncertainties and citations to the original sources of the data. Here we provide all of the measurements in the literature for melting points and boiling points of these elements along with selection of recommended values. We also compiled and evaluated vapor pressures for (just) lithium from the literature and fitted these sets of data from which the boiling point can be accurately determined and computed an enthalpy of vaporization. For values reported prior to 1990, we corrected the values to the International Temperature Scale of 1990 (ITS-90).[1] [2] [3]



## 1.2. Notation Used

In Table 1, we provide definitions for notations used in tables in this work. In general, we utilized the notations as reported in the original sources. Consequently, the following notations for methods “calorimetry, cooling, heat capacity, heat content, thermal, and thermal analysis” may represent the same method, or variations on those methods. We provide here references for some of the methods: scanning calorimetry,[4] differential scanning calorimetry (DSC),[5] adiabatic calorimetry,[6] [7] ice calorimetry,[8] [9] differential thermal analysis (DTA),[10] [11] [12], and pressure-volume-temperature (PVT),[13] [14] [15] sound,[16] [17] density,[18] equilibrium,[19] electrical resistivity,[20] and electrical conductivity.[21] Where the column “Method” is left blank, the method either could not be determined or was not recorded in our compilation.

**Table 1. Notation Used**

Notation	Description		
		ion current	ion current method
adiabatic cal	adiabatic calorimetry	MP	melting point
BP	boiling point	PVT	Pressure-Volume-Temperature method
calorimetry	calorimetry method		
cooling	cooling	resistivity	electrical resistivity method
density	density measurement	review	literature review (not evaluation)
DSC	Differential-Scanning-Calorimetry	sound	sound method
DTA	Differential-Thermal-Analysis	thermal	thermal method
elec conduct	electrical conductivity method	thermal anal	thermal analysis
EOS	Equation-of-State method	thermal cond	thermal conductivity method
equilibrium	Equilibrium method	thermionic	thermionic method
evaluation	evaluated sets of data	TP	triple point
FP	freezing point	volumetric	volumetric method
heat cap	heat capacity	VP	vapor pressure
heat content	heat content	VP fit	fit to vapor pressures
ice calor	ice calorimetry		

### 1.3. International Temperature Scale

The International Temperature Scale of 1990 (ITS-90)[1] is defined by the temperatures of phase equilibrium temperatures of pure substances – 15 fixed points plus vapor-pressure/temperature relations. These include highly accurate melting or freezing points and triple points of mostly atoms (and three molecules). The lowest temperatures on the scale (about 0.65 K to 24.6 K) are defined by vapor- pressure/temperature relations and triple points of  $^3\text{He}$ ,  $^4\text{He}$ , and  $\text{H}_2$ . At higher, but still low temperatures (about 24.6 K to 234.3 K), the temperature scale is defined by the triple points of Ne,  $\text{O}_2$ , Ar, and Hg. The triple point of water which is defined exactly at 273.16 K and is the most important fixed point on ITS-90. At moderate temperatures (about 302.9 K to 692.7 K), the fixed points include the melting point of gallium and the freezing points of In, Sn, and Zn. At the high end of ITS-90, it is defined by the freezing points of Al, Ag, Au, and Cu at about 933.5 K, 1234.9 K, 1337.3 K, and 1357.8 K, respectively. Above the temperatures of these fixed points, ITS-90 is defined by the Planck radiation law using the freezing points of silver, gold, or copper as reference points.

ITS-90 is a “practical” temperature scale, it is an equipment calibration standard, for realization and dissemination of temperatures and it only approximates the true thermodynamic temperatures through “best fit” splined interpolation functions to the fixed points on the ITS-90 scale. Prior practical scales include the International Practical Temperature Scales of 1948 and 1968 (IPTS-48, IPTS-68). Temperature measurements before 1990 need to be corrected to the ITS-90 scale.[1] [2] [3] Below 5.0 K, the temperature scale is realized employing vapor-pressure/temperature relations of  $^3\text{He}$  and  $^4\text{He}$ ; between about 3.0 K and 24.6 K (Ne TP), it is realized using helium gas thermometers; between about 13.8 K ( $\text{H}_2$  TP) and 1234.9 K (Ag FP), it is realized using platinum resistance thermometers; and above about 1234.9 K (Ag FP), it is realized using radiation thermometers.

Although the fixed points are defined exactly, they are just approximations of the true thermodynamic temperatures, albeit highly accurate relative to the thermodynamic temperatures. From 0.6 K to about 17.035 K, the absolute value of the deviations ( $T-T_{90}$ ) generally increase from fractions of a mK (0.01 mK to 0.1 mK) to about 0.29 mK at 17.035 K (from the vapor pressure-temperature relation of equilibrium hydrogen), then monotonically decrease to about -7.3 mK at 161.405 K (Xe TP), then generally increase (with a few small undulations) to about 52.1 mK at 1357.77 K (Cu FP). We note that the difference ( $T-T_{90}$ ) in the ITS-90 scale is zero at the triple point of water at 273.16 K, although future measurements could show a nonzero value. Above the triple point of water, the differences are all positive and increase with temperature: ranging from about +10 mK at 373.124 K ( $\text{H}_2\text{O}$  BP), to +29 mK at 933.473 K (Al FP), and above that are about +(40 to 50) mK up to 1357.77 K (Cu FP). For ( $T-T_{90}$ ) values and their uncertainties above 335 K, see Fischer *et al.* (2011),[22] and for below 335 K, see the recent update by Gaiser *et al.* (2022).[23]

The differences ( $T-T_{90}$ ) have expanded uncertainties of about  $U = (0.24 \text{ to } 0.40) \text{ mK}$  between (0.65 to 5.0) K (from  $^3\text{He}$  and  $^4\text{He}$  vapor-pressure-temperature relations) and 24.5561 K (Ne TP); (0.24 to 0.64) mK between 27.097 K (Ne BP) and 302.9166 K (Ga TP); (1.2 to 2.6) mK between 335 K and 505.078 K (Sn FP); (12 to 15) mK between 600.612 K (Pb MP) to 933.473 K (Al FP); and (28 to

52) mK between 1052.78 K (melting point of the Cu/71.9 % Ag eutectic) and 1357.77 K (Cu FP).[22] [23]

In general, the differences between thermodynamic temperatures and points on the ITS-90 scale ( $T-T_{90}$ ) are somewhat greater than the expanded uncertainties, since points on the ITS-90 scale are interpolated, best fits to minimize overall deviations. The absolute ratios of the uncertainties to the differences  $|U/(T-T_{90})/(T-T_{90})|$  are small (0.4 to 1.2) from 4 K (He VPs) to 35 K (spline point between the triple points of Ne and O<sub>2</sub> at 24.5561 K and 54.3584 K, respectively). The exceptions in this range are there are larger values (1.9 to 3.8) at discontinuities at 5 K, 24.5561 K, and 35 K (He VPs, Ne TP, and a spline point between the triple points of Ne and O<sub>2</sub>, respectively); between 35 K and 77.657 K (near the boiling point of N<sub>2</sub> at 77.352 K), they are small (0.04 to 0.34); from 77.657 K to 335 K (spline point between the triple point of Ga and the boiling point of water at 302.9166 K and 373.124 K, respectively) are very small ranging (0.03 to 0.10). The exception in this range is that there is a discontinuity at 273.16 K (water TP, where  $T-T_{90}$  is zero); between 373.124 K (H<sub>2</sub>O BP) and 505.078 K (Sn FP), the ratios are large (4 to 8); and from 600.612 K (Pb FP) to 1357.77 K (Cu MP), the ratios are comparable (0.8 to 2.2). Again, we note that the differences between thermodynamic temperatures and those on ITS-90 below 335 K were recently updated by Gaiser *et al.* (2022).[23]

### 1.4. Corrections to the Temperature Scale from IPTS-48 and IPTS-68

The temperature corrections ( $\delta$ ) from the IPTS-68 and IPTS-48 temperature scales to the current International Temperature Scale (ITS-90) as given in Table 2 were computed from the work by Rusby *et al.* (1994)[2] which revises values from the 1992 report by Goldberg and Weir[3] in the range (903.765 to 1337.33) K. The revised values for the temperature corrections (from Rusby *et al.*) for both the IPTS-68 and IPTS-48 temperature scales are different from the temperature corrections (from Goldberg and Weir) by (-0.07, -0.31, -0.18, -0.12, and -0.14) K for the boiling points of (Na, K, Rb, Cs, and Fr), respectively, because these boiling points lie in the range (903.765 K to 1337.33 K) of the revised values.

As can be seen in Table 2, the corrections for the melting points are much smaller than the uncertainties in the melting points. The corrections for the boiling points of Li, Na, K, and Cs are on the order of the uncertainties in the boiling points (because the boiling points are high), while for Rb and Fr, the corrections are much smaller than the uncertainties in the boiling points (because the uncertainties are high).

**Table 2. Recommended values for the melting points and boiling points of the alkali metals. Expanded uncertainties  $U$  ( $2\sigma$ , 95 % coverage), and corrections from IPTS-68 and IPTS-48 to the ITS-90 Temperature Scale ( $T_{90}$ ).**

Atom	trs	$T_{\text{trs}}/\text{K}$	$U(T_{\text{trs}})/\text{K}$	$\delta T_{90-68}/\text{K}$	$\delta T_{90-48}/\text{K}$
Li	MP	453.61	0.14	-0.04	+0.00
Na	MP	370.93	0.06	-0.03	-0.03
K	MP	336.84	0.24	-0.02	-0.03
Rb	MP	312.46	0.18	-0.01	-0.02
Cs	MP	301.66	0.20	-0.01	-0.02
Fr	MP	300	3	-0.01	-0.02
Li	BP	1617.2	3.3	-0.36	+1.54
Na	BP	1156.09	0.19	-0.02	+0.88
K	BP	1030.87	0.7	+0.04	+0.59
Rb	BP	960	2	-0.04	+0.31
Cs	BP	941.4	0.4	-0.07	+0.24
Fr	BP	936	6	-0.08	+0.22

**Note:** For IPTS-68, the corrections ( $\delta T_{90-68}$ ) decrease monotonically from about -0.006 K at 298 K to about -0.125 K at about 903.75 K. Then there is a discontinuity in  $\delta(T)$  at 903.75 K (near the freezing point of antimony) when the slope ( $d\delta/dT$ ) in the temperature scale changes from negative to positive,  $\delta_{90-68}(T)$  then maximize at about +0.051 K at about 1060 K, and then decrease monotonically with increasing temperatures. They are about +0.00 K at 1140 K, -0.56 K at 2000 K, and -1.26 K at 3000 K.

### **1.5. Uncertainties**

The uncertainties given here for the recommended values are expanded uncertainties ( $U$ ) at the 95 % confidence level ( $2\sigma$ ) are assigned based on our judgment of the range of reliable values (Type B uncertainties), see Taylor and Kuyatt (1994).[24] Uncertainties in the tables given in parentheses are our estimates. Where uncertainties were not available, either the notation “na” was used or left blank.

## 2. Alkali Metals Melting Points

### 2.1. Overview

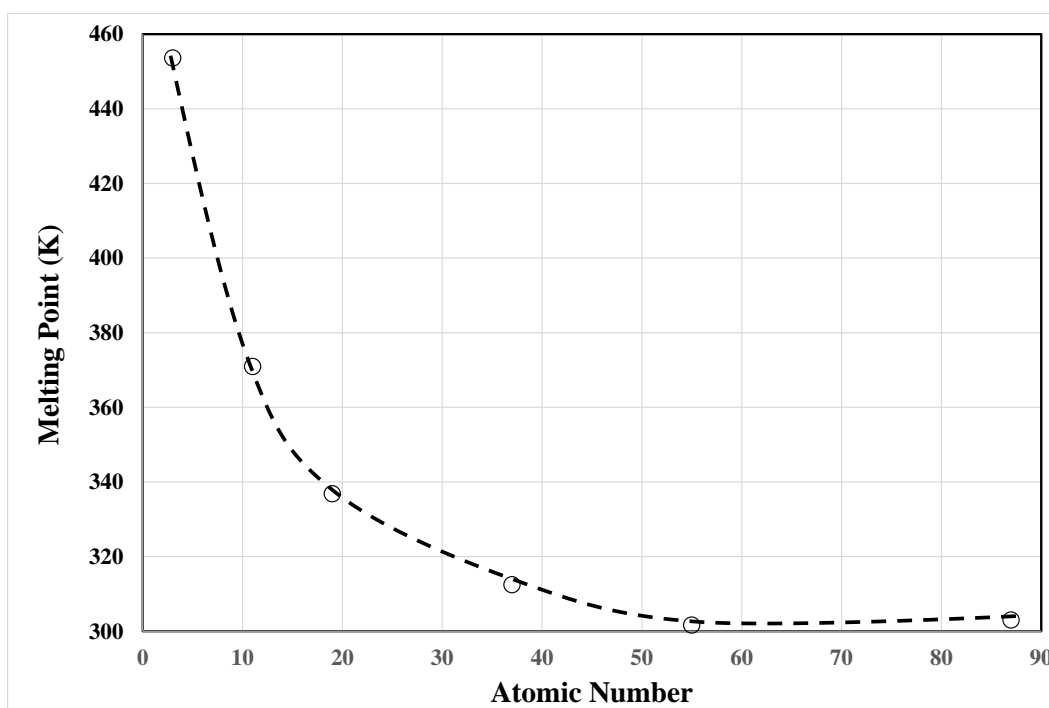
In this section, we provide recommended values for the normal melting points (at 1 atm = 101.325 kPa) of the alkali metals: lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), and francium (Fr). We first provide a summary of recommended melting points for the alkali metals in Table 3 and Figure 1. Then we provide individual tables of compiled melting points from the literature for each of the alkali metals.

As can be seen in Table 3 and Figure 1, the melting points of the alkali metals decrease with atomic number with the melting point of lithium higher than the trend. Increasing atomic radius causes the distance between the nucleus and delocalized electrons to increase, which weakens bonding. Lithium has an elevated melting point compared to the rest of the alkali metals. It is a very small element with an electronic configuration of  $1s^2 2s^1$  having only two shells and just 3 electrons; thus, there are stronger attractive forces between the shells and, consequently, strengthened bonding. The melting point of francium is an estimate based on the trend in melting points and atomic radii, and just slightly different than that for cesium.

In the tables, we have included sources of melting points where the data was not abstracted by the time of publication because of time constraints – at a later date, these data should be abstracted.

**Table 3. Recommended values for the melting points of the alkali metals.**

Atomic #	Atom	$T_m(\text{K})$	$U(T_m/\text{K})$
3	Li	453.61	0.14
11	Na	370.93	0.06
19	K	336.84	0.24
37	Rb	312.46	0.18
55	Cs	301.66	0.20
87	Fr	300	3



**Figure 1. Trend in melting points of the alkali metals.**

## 2.2. Lithium (Li) Melting Point

The melting point of lithium has been measured with high precision by several groups ranging from 453.6 K to 453.69 K by Hubberstey and coworkers (1976), [25] [26] Creffeld *et al.* (1974), [20] and Douglas *et al.* (1955). [27] Creffeld *et al.* measured the melting point by monitoring the electrical resistivity, while the other three groups used thermal methods. We select the value of  $T_m = 453.61 \pm 0.14$  K from the resistivity measurements of Creffeld *et al.* (1974) [20]. We increased the uncertainty (0.08 to 0.14) K assigned by Creffeld *et al.* to reflect the range of other values. This value is statistically identical to that reported by Hubberstey and coworkers and to our unweighted average of values. This value is only slightly lower than, but still consistent with earlier measurements by Douglas *et al.* (1955) [27] and Luedemann and Kennedy. [28] There are a number of other older measurements that are slightly lower – ranging (452 to 453) K, as well as a few outliers.

We have corrected values to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are - 0.04 K and +0.00 K, respectively. Ohse *et al.* (1985) [29] apparently did not correct the compiled literature values to IPTS-68. In order to verify this lack of corrections, we compared their values to other values and found that Ohse *et al.* values are identical to earlier work: the boiling points of Na, K, and Cs from Stone *et al.* (1966) [30] and the boiling points of Li and Cs from Bohdansk (1965). [31]

The melting point values for lithium are provided in Table 4 and Figure 2. The recommended melting point  $T_m = 453.61 \pm 0.14$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are all within the recommended uncertainty. The distinct outliers ( $>4\sigma$ ) differ by about (0.6 to 1.5) K from the recommended value.



**Table 4. Melting Points of Lithium (Li)**

$T_m(\text{Li})/\text{K}$	$T_{90}/\text{K}$	$U(T_m)/\text{K}$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
<b>453.61</b>	<b>453.61</b>	<b>0.14</b>	<b>Recommended</b>	<b>selected 1974CRE</b>	<b>This work</b>
453.76	453.76		volumetric		1978NIK [32]
453.64	453.60	0.02	thermal		1976HUB [25]
453.64	453.60	0.03	thermal		1976ADA [26]
453.65	453.61	0.08	resistivity		1974CRE [20]
453.5	453.5	(0.3)	thermal		1968LUE [28]
453.69	453.69	na	thermal		1963HIC [33]
453.7	453.7	0.5	thermal		1958KEL [34]
453.69	453.69	0.03	heat capacity		1955DOU [27]
453.4	453.4	0.1	thermal	quoted in 1955EVA	1935LOS [35]
453	453				1855BUN [36]
<b>Other values</b>					
453.6	453.6	0.4	unweighted avg		This work
454.2	454.2	na	EOS		2012NIE [37]
454.9	454.9		thermal		1963WEA [38]
455	455	1.5	thermal		1961PON [39]
452	452	1	calorimetry		1952KIL [40]
452.65	452.65		heat capacity		1950KUB [41]
453	453		thermal		1950CAB [42]
452	452		resistivity	extracted from graph	1926BRI [43]
452.2	452.2		thermal		1911ZUK [44]
453.2	453.2		heat capacity		1906THU [45]
453.2	453.2			quoted in 1955EVA	1906RUF [46]
455	455		heat capacity		1906KLE [47]
459	459				1900KAH [48]
463	463				1896GUN [49]
<b>Reviews and evaluations</b>					
453.7	453.7	na	review		2020RUM [50]
453.69	453.69		review		1998CHA [51]
453.65	453.61	0.05	evaluation		1994ALC [52]
453.64	453.60	0.1	evaluation		1985OHS [29]
453.7	451.7		review		1975VAR [53]
453.7	451.7		review		1974HO [54]
453.7	451.7		review		1973HUL [55]
453.69	451.69		review		1970SHP [56]
453.69	453.69		review		1955EVA [57]
439	439	na	evaluation		1941DIT [58]
459	459		review		1919GUE [59]
<b>To abstract</b>					
–					1950KUB [41]
–					1900KAH [48]

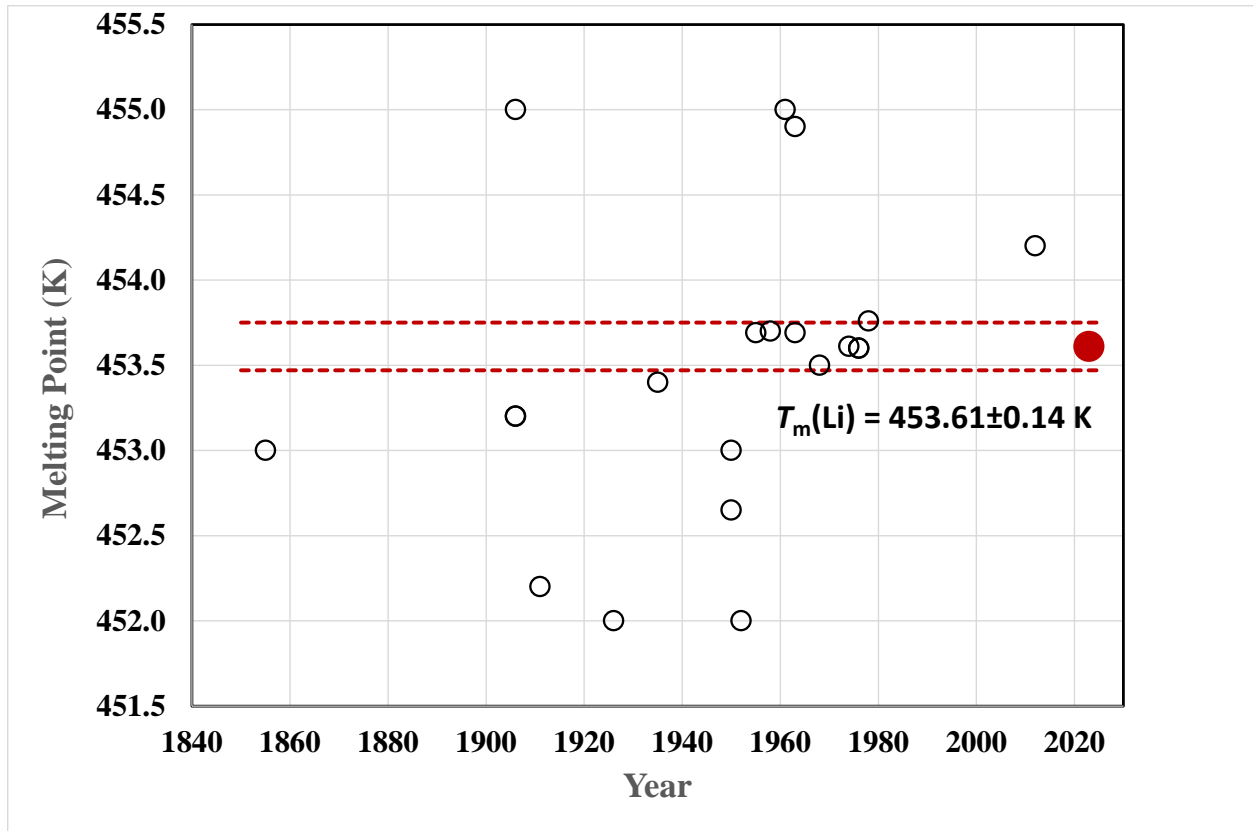


Figure 2. Melting point values and recommendation for lithium. The solid point is the recommended value and the dotted lines represent the expanded uncertainty.

### 2.3. Sodium (Na) Melting Point

The melting point of sodium has been measured with good-to-high precision by many groups ranging  $T_m = (370.65 \text{ to } 371.15) \text{ K}$ . An unweighted average of the most reliable values is  $T_m = 371.0 \pm 0.2 \text{ K}$ . We have corrected all of the values to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are both  $-0.03 \text{ K}$ .

The BIPM/CCT (Bureau International des Poids et Mesures/Consultative Committee for Thermometry) working group recommends a value of  $T_m = 370.944 \pm 0.01 \text{ K}$  with a very small uncertainty, see Bedford *et al.* (1996)[60]. The CCT report on which this value is based, however, is not readily available, see Butkiewicz and Gizmajer (1980).[61] We select a value of  $T_m = 370.93 \pm 0.06 \text{ K}$  from the ice calorimetry measurements (a method with usually high precision) of Ginnings *et al.* (1950)[8] assigning a slightly higher uncertainty than reported (0.03 K) to reflect the range of other reliable values This value is consistent with the CCT recommendation and with other reliable measurements: the speed of sound measurements by Kamikoka (1983),[16] and the thermal measurements by Fritsch and Luscher (1972)[62] and Anderson *et al.* (1971).[63] It is also consistent with the (rough) equation-of-state (EOS) determination by Nie *et al.*,[37] who do not provide an uncertainty.

The melting point values for sodium are provided in Table 5 and Figure 3. The recommended melting point  $T_m = 370.93 \pm 0.06 \text{ K}$  is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are statistically identical to the recommended value. There are a few distinct outliers ( $>4\sigma$ ) that differ by about (0.1 to 0.25) K from the recommended value – many of them being lower, suggesting melting point depression due to impurities.

**Table 5. Melting Points of Sodium (Na)**

$T_m(\text{Na})/\text{K}$	$T_{90}/\text{K}$	$U(T_m)/\text{K}$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
<b>370.93</b>	<b>370.93</b>	<b>0.06</b>	<b>Recommended</b>	<b>Selected 1950GIN</b>	<b>This work</b>
371.2	371.2	na	EOS		2012NIE [37]
370.95	370.92	0.1	sound	quoted in 1985OHS	1983KAM[16]
370.97	370.94	0.01	resistivity		1980BUT [61]
370.92	370.89	0.04	thermal cond		1972FRI [62]
371.05	371.02	0.02	thermal		1971AND [63]
371.05	371.02	0.02	thermal		1970GOA [64]
371.05	371.02				1969HSU [65]
371.0	371.0	(0.3)	thermal		1968LUE [28]
371.018	370.988	0.01	adiabatic calor	1.25 bar	1967MAR[66]
370.97	370.94			quoted in 1955EVA	1952DOU [67]
370.96	370.93	0.03	ice calorimetry		1950GIN [8]
370.9	370.9			quoted in 1955EVA	1935LOS [35]
370.9	370.9			quoted in 1955EVA	1935GOR [68]
370.95	370.92	0.1	thermal analysis		1930LAD [69]
370.85	370.82	0.05	VP		1927EDM [70]
371.05	371.02	0.05	calorimetry	quoted in 1955EVA	1913REN [71]
370.8	370.8		heat content	quoted in 1955EVA	1905BER [72]
371.0	371.0			quoted in 1955EVA	1889TAM [73]
<b>Other values</b>					
371.0	371.0	0.2	unweighted avg		This work
370.75	370.72	na	thermal analysis		1976MIR [74]
371.2	371.2			quoted in 1955EVA	1936GRU [75]
370.78	370.75		thermal analysis	quoted in 1950GIN	1926BRI [43]
370.76	370.73	na	thermal		1914GRI [76]
370.7	370.7	(0.15)	volumetric		1914BRI [77]
370.7	370.7			quoted in 1955EVA	1912VAN [78]
369.7	369.7		heat content	quoted in 1955EVA	1887JOA [79]
369.9	369.9			quoted in 1927EDM	1883HAG [80]
<b>Reviews and evaluations</b>					
370.944	370.944		review		2020RUM[50]
370.98	370.98	0.02	review		1998CHA [51]
370.944	370.944	0.01	evaluation		1996BED [60]
370.95	370.95	0.05	evaluation		1994ALC [52]
370.90	370.87	0.1	evaluation		1985OHS [29]
370.97	370.94		review		1979FOU [81]
371.0	371.0		review		1975VAR [53]
371	371		review		1973HUL [55]
371	371		review		1970SHP [56]
370.98	370.95	na	evaluation		1963HIC [33]
370.97	370.94		review		1955EVA [57]
370	370	Na	review		1941DIT [58]
<b>Other values</b>					
–					1996OTT [82]
–					1970GOA [83]
–					1967GOL [84]

-					1938HAL [85]
-					1913REN [71]

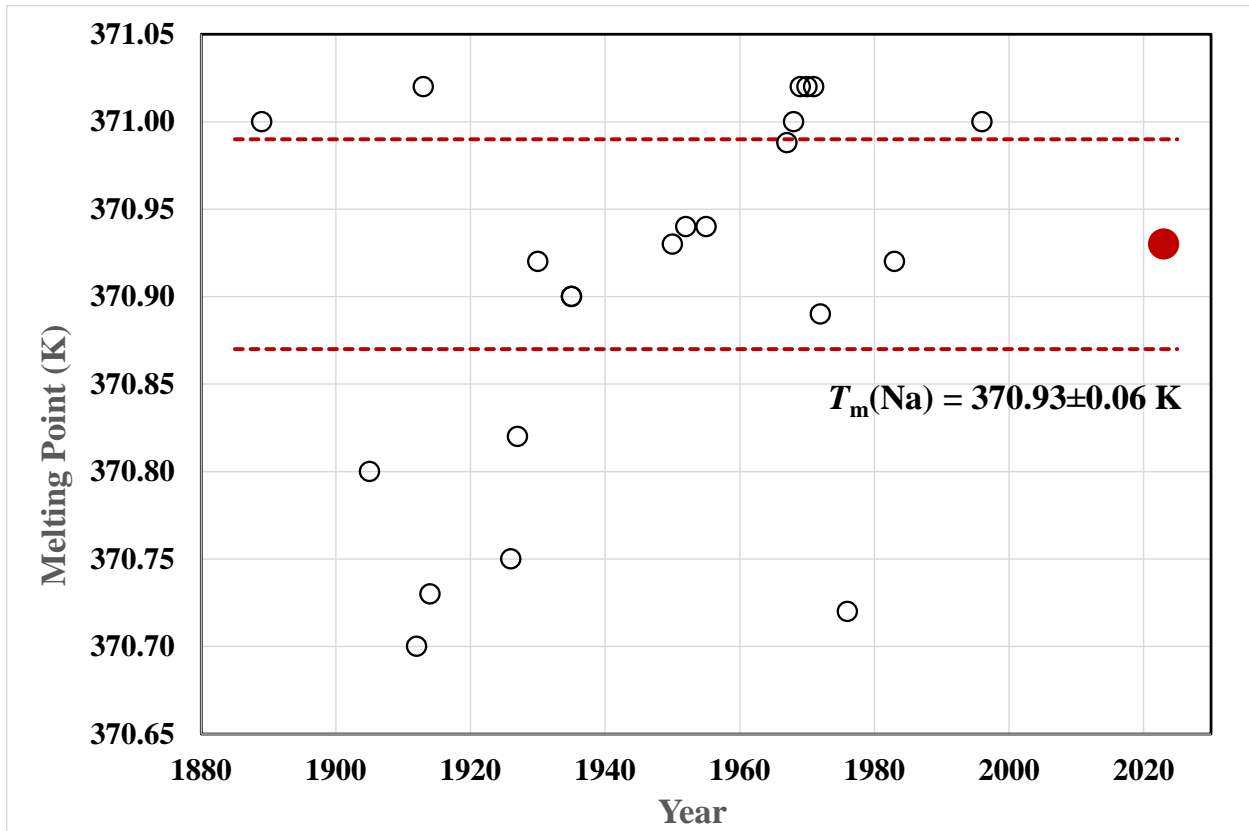


Figure 3. Melting point values and recommendation for sodium. The solid point is the recommended value, and the dotted lines represent the expanded uncertainty.

## 2.4. Potassium (K) Melting Point

There are fair number of accurate determinations for the melting point of potassium ranging about 335 K to 337 K with an unweighted average of about  $336.3 \pm 1.0$  K; eliminating lower temperature points likely influenced by impurities, the unweighted average is about  $336.7 \pm 0.3$  K. We select the very accurate value from Ott and coworkers reported in several publications [64] [65] [86] [83] [87] of  $T_m = 336.84 \pm 0.24$  K, assigning a higher uncertainty than the very small value that they report (0.02 K) in order to account for the range of other reliable values. This value is statistically identical to our unweighted averages. In Table 6, we have corrected all of the values to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are -0.02 K and -0.03 K, respectively.

The melting point values for potassium are provided in Table 6 and Figure 4. The recommended melting point  $T_m = 336.84 \pm 0.24$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are statistically identical to the recommended value. There are a few distinct outliers ( $>4\sigma$ ) that differ by about (0.4 to 1.5) K from the recommended value – all of them lower, suggesting melting point depression due to impurities.

**Table 6. Melting Points of Potassium (K)**

$T_m(K)/K$	$T_{90}/K$	$U(T_m)/K$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
<b>336.84</b>	<b>336.84</b>	<b>0.24</b>	<b>Recommended</b>	<b>Selected 1971GOA</b>	<b>This work</b>
336.96	336.94		volumetric		1978NIK [32]
336.86	336.84	0.02	MP plateau		1971GOA [87]
336.86	336.84	0.02	MP plateau		1971DEL [88]
336.9	336.9		resistivity		1971ADD [89]
336.86	336.84	0.02	cooling		1970GOA [83]
336.86	336.84	0.02	MP plateau		1970AND [64]
336.86	336.84	0.02	MP plateau		1969OTT [86]
336.45	336.43	0.2	density	quoted in 1985OHS	1969BAS [90]
336.4	336.4		elec conduct		1966GRO [21]
336.35	336.32	0.1	heat capacity		1952DOU [67]
336.9	336.9		volumetric		1946WAL [91]
336.50	336.47		heat capacity		1939CAR [92]
336.80	336.77	0.05	thermal		1927EDM [70]
336.65	336.62	0.05	calorimetry	quoted in 1985OHS	1913REN [71]
336.8	336.8		melting point		1907SMI [93]
<b>Other values</b>					
336.7	336.7	0.3	unweighted avg		This work
337.8	337.8	na	EOS		2012NIE [37]
336.0	336.0	(1.1)	thermal		1968LUE [28]
336.15	336.12		thermal		1960GRA [94]
335.7	335.7	(0.6)	volumetric		1914BRI [77]
335.7	335.7		melting point	quoted in 1952DOU	1912VAN [78]
335.15	335.12		heat capacity	quoted in 1955EVA	1905BER [72]
335.7	335.7		melting point	quoted in 1914BRI	1902KUR [95]
335.3	335.3		melt vs press	quoted in 1914BRI	1898HEY [96]
335.7	335.7		melting point	quoted in 1914BRI	1894HOL [97]
331.15	331.12		calorimetry	quoted in 1955EVA	1887JOA [79]
335.3	335.3	na	volumetric	quoted in 1914BRI	1883HAG [80]
<b>Reviews and evaluations</b>					
336.55	336.55		review		2020RUM [50]
336.35	336.35		review		1998CHA [51]
336.6	336.6	0.2	evaluation		1994ALC [52]
336.55	336.53	0.2	review		1985OHS [29]
336.4	336.4		review		1975VAR [53]
336.8	336.8		review		1974HO/POW [54]
336.35	336.33		review		1973HUL/DES [55]
336.6	336.6		review		1970SHP/YAK [56]
336.4	336.4	na	evaluation		1963HIC [33]
336.35	336.32		review		1955EVA/JAC [57]
335	335	na	review		1941DIT/GIL [58]
335.6	335.6		review	quoted in 1952DOU	1919GUE [59]
<b>To abstract</b>					
–					1996OTT [82]
–					1913REN [71]



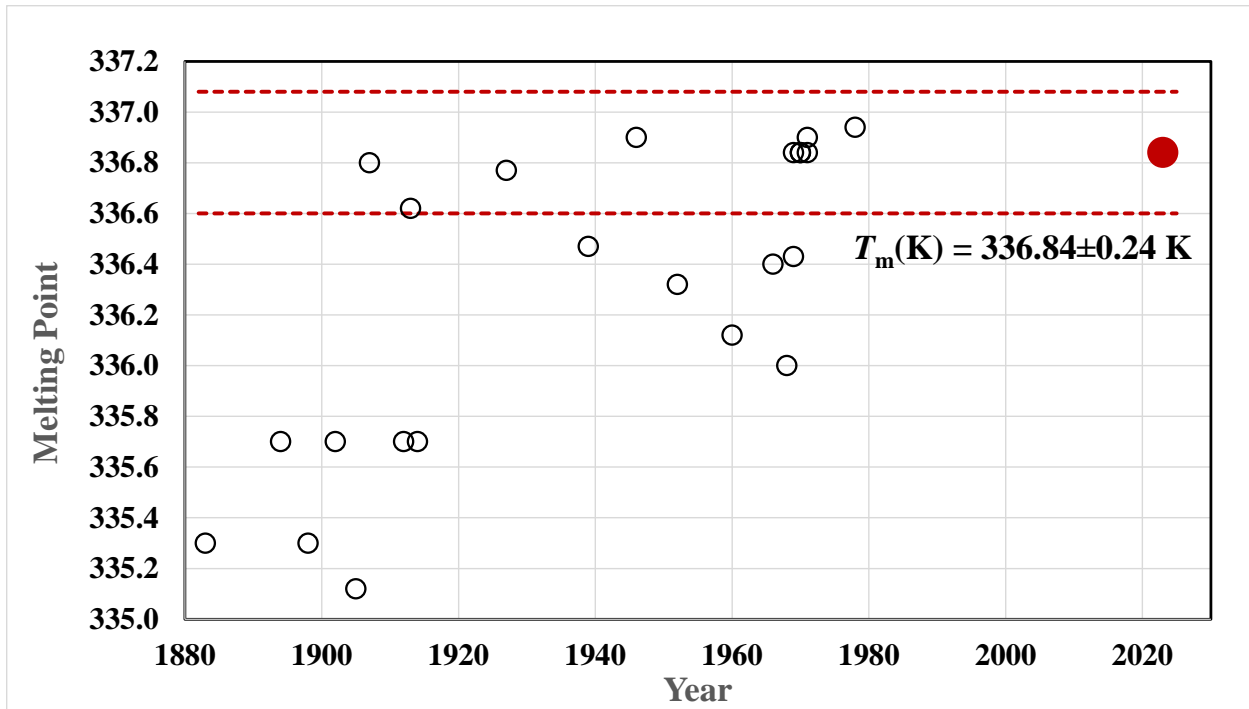


Figure 4. Melting point values and recommendation for potassium. The solid point is the recommended value, and the dotted lines represent the expanded uncertainty.

## 2.5. Rubidium (Rb) Melting Point

There are a fair number of good-to-high precision determinations of the melting point of rubidium ranging from about 311.9 K to 312.65 K. An unweighted average of these values is about  $313.27 \pm 0.38$  K. We select the very accurate value of  $312.46 \pm 0.18$  K from Martin (1970)[18] and assign a higher uncertainty than the small value reported (0.02 K) in that work to reflect the range of other reliable values. We note that Ott and coworkers report the same value in several publications: Goates *et al.* (1969, 1970, 1971),[83] [87] [98] Anderson *et al.*,[64] and Hsu,[65] – thus, these are not independent determinations. In Table 7, we corrected the melting points of all values to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are -0.01 K and -0.02 K, respectively.

The melting point values for rubidium are provided in Table 7 and Figure 5. The recommended melting point  $T_m = 312.46 \pm 0.18$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are statistically identical to the recommended value. There are a few distinct outliers ( $>4\sigma$ ) that differ by about (0.4 to 0.65) K from the recommended value – all of them lower, suggesting melting point depression due to impurities.

**Table 7. Melting Points of Rubidium (Rb)**

$T_m(\text{Rb})/\text{K}$	$T_{90}/\text{K}$	$U(T_m)/\text{K}$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
<b>312.46</b>	<b>312.46</b>	<b>0.18</b>	<b>Recommend</b>	<b>Selected 1970MAR</b>	<b>This work</b>
312.47	312.47	na	EOS		2006MOZ [99]
312.12	312.11		volumetric		1978NIK [32]
312.47	312.46	0.02	calorimetry		1971GOA [87]
312.45	312.44	0.5	calorimetry		1971DEL [88]
312.47	312.46	0.02	calorimetry		1970MAR [18]
312.45	312.44	0.02	thermal		1970GOA [83]
312.45	312.44	0.02	thermal		1970AND [64]
312.45	312.44	na	thermal		1969HSU [65]
312.45	312.44	0.02	thermal		1969GOA [98]
312.31	312.30	0.05	density	quoted in 1985OHS	1969BAS [90]
312.65	312.63	0.01	thermal	quoted in 1985OHS	1965FIL [100]
312.54	312.52		MP plateau		1963WEA [38]
311.90	311.88	0.5	thermal	quoted in 1985OHS	1955DAU [101]
312.0	312.0	na		quoted in 1969HSU	1935GOR [68]
311.9	311.9	na		at 1 kg/cm <sup>2</sup>	1926BRI [43]
312.15	312.13	0.05	calorimetry	quoted in 1985OHS	1913REN [71]
<b>Reviews and evaluations</b>					
312.5	312.5		review		2020RUM [50]
312.65	312.64	0.1	review		1998CHA [51]
312.45	312.45	0.10	evaluation		1994ALC [52]
312.65	312.64	0.1	evaluation		1985OHS/BAB [29]
312.7	312.7		review		1975VAR [53]
312.04	312.03		review		1974HO/POW [54]
312.64	312.63		review		1973HUL/DES [55]
312.65	312.64		review		1970SHP/YAK [56]
311	311	na	review		1941DIT/GIL [58]
<b>To abstract</b>					
–					1996OTT [82]
–					1970GOA [83]
–					1913REN [71]

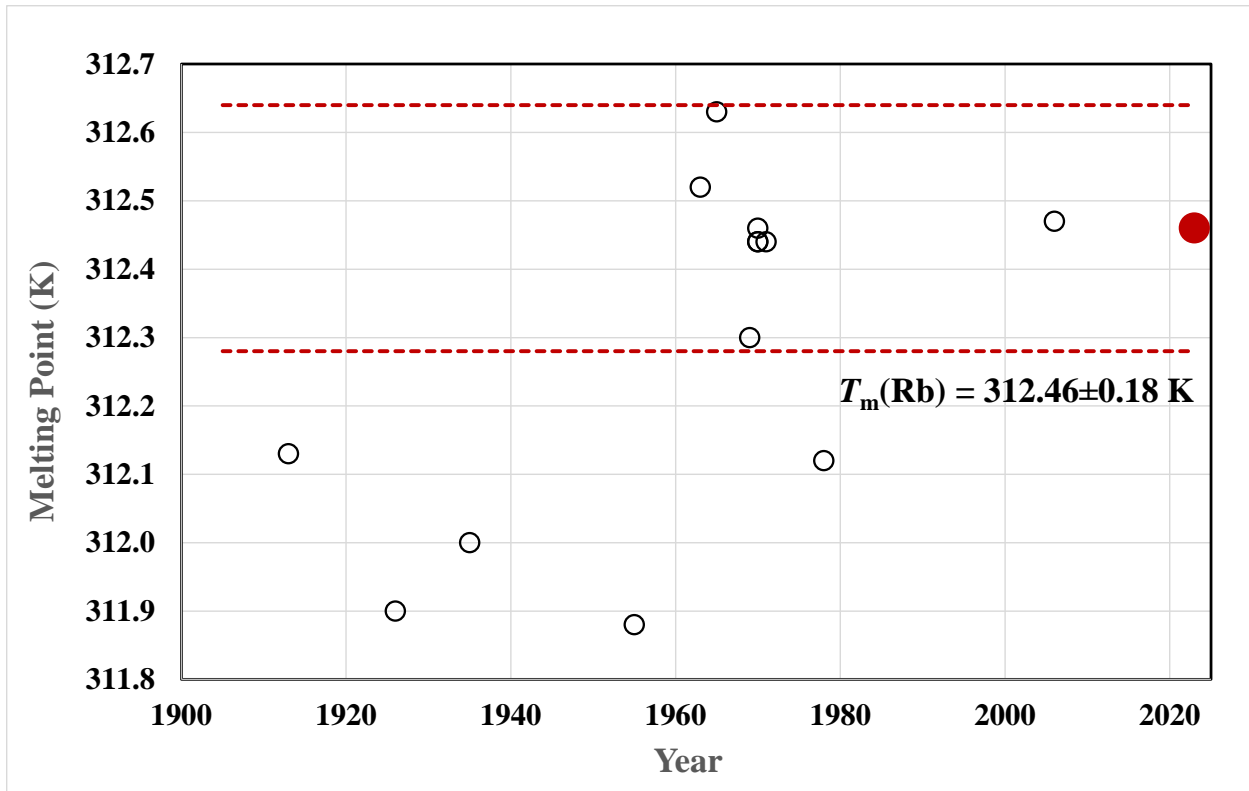


Figure 5. Melting point values and recommendation for rubidium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.

## 2.6. Cesium (Cs) Melting Points

For cesium, considering only melting point values with low reported uncertainties ( $<0.2$  K), an unweighted average is about  $301.70 \pm 0.20$  K. We select the very accurate value of  $301.66 \pm 0.20$  K reported by Martin (1970)[18] assigning a slightly higher uncertainty than reported (0.13 K) to reflect the range in other values. We note that we also selected the melting point for rubidium (Rb) from the work of Martin suggesting that their measurements are reliable. In Table 8, we corrected the melting points of all values to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are  $-0.01$  K and  $-0.02$  K, respectively.

The melting point values for cesium are provided in Table 8 and Figure 6. The recommended melting point  $T_m = 301.66 \pm 0.20$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. Almost all of the reported values are within  $3\sigma$  of the recommended value, save the DTA measurement of Kennedy *et al.* (1962)[102] which differs by about  $5\sigma$ .

**Table 8. Melting Points of Cesium (Cs)**

$T_m(\text{Cs})/\text{K}$	$T_{90}/\text{K}$	$U(T_m)/\text{K}$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
<b>301.66</b>	<b>301.66</b>	<b>0.20</b>	<b>Recommended</b>	<b>Selected 1970MAR</b>	<b>This work</b>
301.67	301.66	0.13	density		1970MAR [18]
301.59	301.58	1	thermal analysis		1970GOA [64]
301.55	301.53	0.01	heat capacity		1965FIL [100]
302.15	302.13	na	DTA		1962KEN [102]
301.79	301.77	0.17	ice calorimetry		1954CLU [103]
301.75	301.73	na	ion current		1937TAY [104]
301.95	301.93	0.1	thermal analysis		1935LOS [35]
301.45	301.43		thermal analysis		1934RIN [105]
301.75	301.73		thermal analysis		1930DEB [106]
301.6	301.6	0.05	calorimetry		1913REN [71]
<b>Reviews and evaluations</b>					
301.65	301.65		review		2020RUM [50]
301.6	301.6	0.10	evaluation		1994ALC [52]
301.6	301.6	0.05	evaluation		1985OHS [29]
301.6	301.6		review		1975VAR [53]
301.55	301.54		review		1973HUL [55]
301.55	301.54		review		1970SHP [56]
299	299	na	evaluation		1941DIT [58]
<b>To abstract</b>					
–					1996OTT [82]
–					1963TEP [107]
–					1913REN [71]

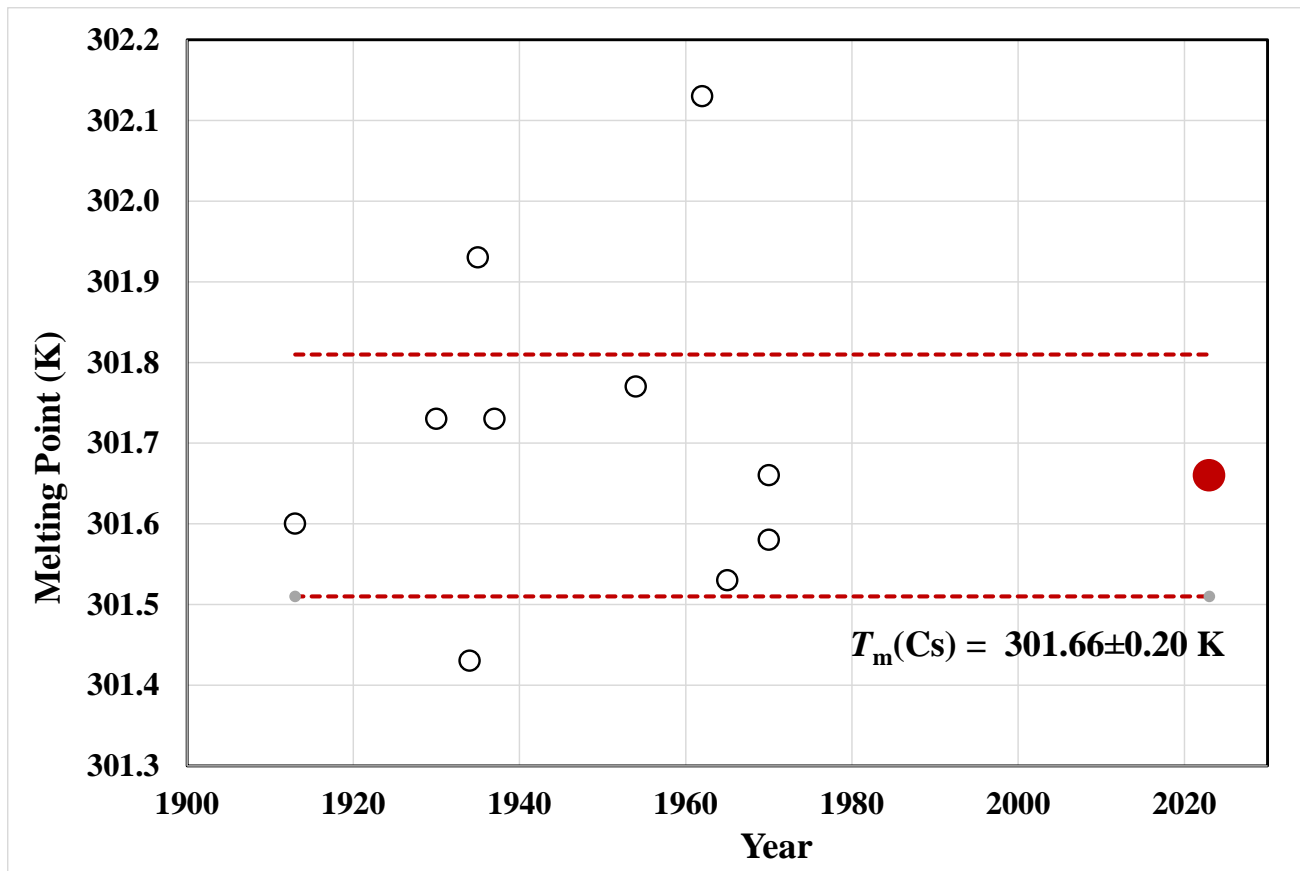


Figure 6. Melting point values and recommendation for cesium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.

## 2.7. Francium (Fr) Melting Point

Various estimated values for the melting point of francium can be found in the literature, [50] [108] [109] [110] [110] [111] mainly from Russian journals, and on the internet, ranging from about 294 K to 302 K – the most often quoted value is 300 K. All of the estimates are based on trends in melting points of the other alkali metals or from other correlations. The melting point must be estimated, because francium has no stable isotopes and cannot be isolated. The most recent and systematic study is the work by Oshchapovskii (2014)[112] which estimated the melting point using trends in the melting points of the alkali metal halides and provides a value of  $298.0 \pm 0.5$  K. Based on decreasing successive differences in the melting points of the alkali metals, we estimate that the melting point of francium to be about 303 K (1 K higher than that for cesium). Based on trends in melting points with Van der Waals and covalent radii,[50] we estimate the melting point for francium to be 301.4 K and 299.4 K, respectively. Consequently, we adopt an average of these two latter values  $T_m = 300 \pm 3$  K (2 K lower than that for cesium), see Table 9.

**Table 9. Melting Points of Francium (Fr)**

$T_m(\text{Fr})/\text{K}$	$T_{90}/\text{K}$	$U(T_m)/\text{K}$	Method	Notes	Reference
<b>300</b>	<b>300</b>	<b>3</b>	<b>Recommended</b>	<b>Est from radii corr</b>	<b>This work</b>
298.0	298.0	0.5	correlation metal halides		2014OSH[112]
<b>To abstract</b>					
–					2023ROY [113]



### 3. Alkali Metals Boiling Points

#### 3.1. Overview

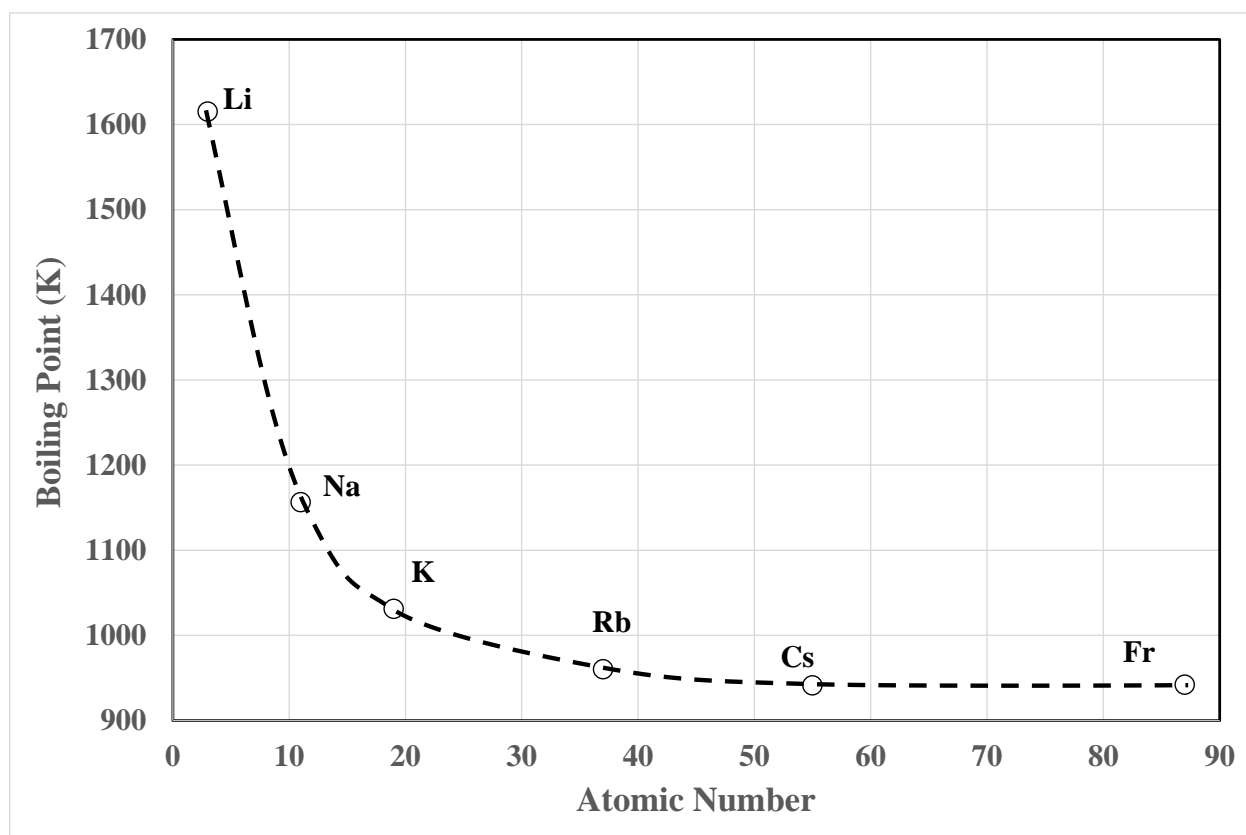
In this section, we provide recommended values for the normal boiling points (at 1 atm = 101.325 kPa) of the alkali metals: lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), and francium (Fr). We first provide a summary of recommended boiling points for the alkali metals in Table 10 and Figure 7. Then we provide individual tables of compiled boiling points from the literature for each of the alkali metals. Note that we provide a boiling point for lithium based on fits to vapor pressure data. For other alkali metals, the boiling points were derived from reported boiling points in the literature – at a later date, we will derive boiling points from fits to vapor pressure data.

As can be seen in Table 10 and Figure 7, the boiling points of the alkali metals decrease with atomic number with the boiling point of lithium higher than the trend. Increasing atomic radius causes the distance between the nucleus and delocalized electrons to increase, which weakens bonding. Lithium has an elevated boiling point compared to the rest of the alkali metals. It is a very small element with an electronic configuration of  $1s^2 2s^1$  having only two shells and just 3 electrons; thus, there are stronger attractive forces between the shells and, consequently, strengthened bonding. The boiling point of francium is an estimate based on the trend in boiling points and atomic radii, and just slightly different than that for cesium.

In the tables, we have included sources of boiling points and vapor pressures where the data was not abstracted by the time of publication because of time constraints – at a later date, these data should be abstracted.

**Table 10. Recommended values for the boiling points of the alkali metals.**

Atomic #	Atom	$T_b/K$	$U(T_b)/K$
3	Li	1617.2	3.3
11	Na	1156.09	0.19
19	K	1030.87	0.7
37	Rb	960	2
55	Cs	941.4	0.4
87	Fr	936	6



**Figure 7. Trend in boiling points of the alkali metals.**

### 3.2. Lithium (Li) Boiling Point

The normal boiling point of lithium has been measured with fair precision (2 to 3) K by several groups ranging about  $T_b = (1613 \text{ to } 1618)$  K. An unweighted average of all the experimental data in Table 11 is about  $1614.3 \pm 5$  K. When excluding outliers ( $>3\sigma$ ), the unweighted average is about  $1616 \pm 2.5$  K. A more accurate determination of the boiling point of lithium can be derived from fitting a set of vapor pressure curves, see the following subsection “Alkali Metal Vapor Pressures.”

We have corrected values to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are  $-0.36$  K and  $+1.54$  K, respectively. Ohse *et al.* (1985)[29] apparently did not correct the compiled literature values to IPTS-68. Considering boiling points provided Ohse *et al.* compared to other values to verify the lack of correction to IPTS-68, we found that the values for the boiling points of Na, K, and Cs are identical in earlier work by Stone *et al.* (1966)[30] and Ohse *et al.* Similarly, the boiling points for Li and Cs in Ohse *et al.* and that derived from vapor pressures in earlier work by Bohdanski (1965)[31] are the same.

The boiling point values for lithium are provided in Table 11 and Figure 8. The recommended boiling point  $T_b = 1617.2 \pm 3.3$  K (from fits to sets of vapor pressure curves) is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are statistically identical to the recommended value. The distinct outliers ( $>4\sigma$ ) differ by about (0.6 to 1.5) K from the recommended value.

**Table 11. Boiling Points of Lithium (Li)**

$T_b(\text{Li})/\text{K}$	$T_{90}/\text{K}$	$U(T_b)/\text{K}$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
<b>1617.2</b>	<b>1617.2</b>	<b>3.3</b>	<b>Recommended (VP fits)</b>	<b>0.1-16 bar</b>	<b>This work</b>
1609.1	1608.7		evaluation (VP fits)	0.1-1.8 bar	1988WIL [114]
1613.9	1615.4		VP	4-1500 mbar	1969ANI [115]
1607	1609	3	VP	0.1-16 bar	1968SHP [116]
1617.0	1618.5		VP	130-4800 mbar	1965BOH [31]
1616.1	1617.6		VP	0.1-7 bar	1965RIG [117]
1618.5	1620.0	5	VP	20-110 mbar quoted 1936GOR	1929HAR [118]
<b>Other values</b>					
1616.0	1616.0	2.5	unweight avg (BPs)	0.1-16 bar	This work
1590	1590	10	VP	0.4-1.3 Pa	2001ZAI [119]
1633	1633	6	VP	0.9-3.4 mbar	1989ZOB [120]
1608.2	1607.9	na	VP	2.8-8.3 bar	1982RAJ [121]
1608.7	1608.4	5.9	VP	0.1-13 bar	1971SCH [122]
1616.7	1618.2		VP	0.5-1.9 bar	1966STO [123]
1613.9	1615.4	3	VP fit	0.2-1 bar	1963HIC [33]
1599.8	1601.3	0.6	VP fit	0.1-120 mbar	1955DOU [27]
<b>Reviews and evaluations</b>					
1615	1615		review		2020RUM [50]
1614.40	1614.40	na	evaluation		2006VEL [124]
1613	1613	2.0	evaluation		1985OHS [29]
1607.9	1607.5		evaluation	0.1-1.8 bar	1988WIL [114]
1615	1615		evaluation		1975VAR [53]
1615	1615		evaluation		1973HUL [55]
1609	1609		evaluation (VP fits)		1973HUL [55]
1611.6	1611.3		evaluation		1970SHP [56]
1597.6	1599.1	0.3	evaluation VP	70-3300 mbar	1968DAV [125]
1591	1593	na	evaluation (VP fits)	3-1050 mbar	1941DIT [58]
1618.6	1620.1	5	evaluation (VP fits)	20-110 mbar	1936GOR [126]
1645	1647	na	evaluation		1935KEL [127]
<b>To abstract</b>					
-					1988ZOB [128]
-					1939MAU [129]

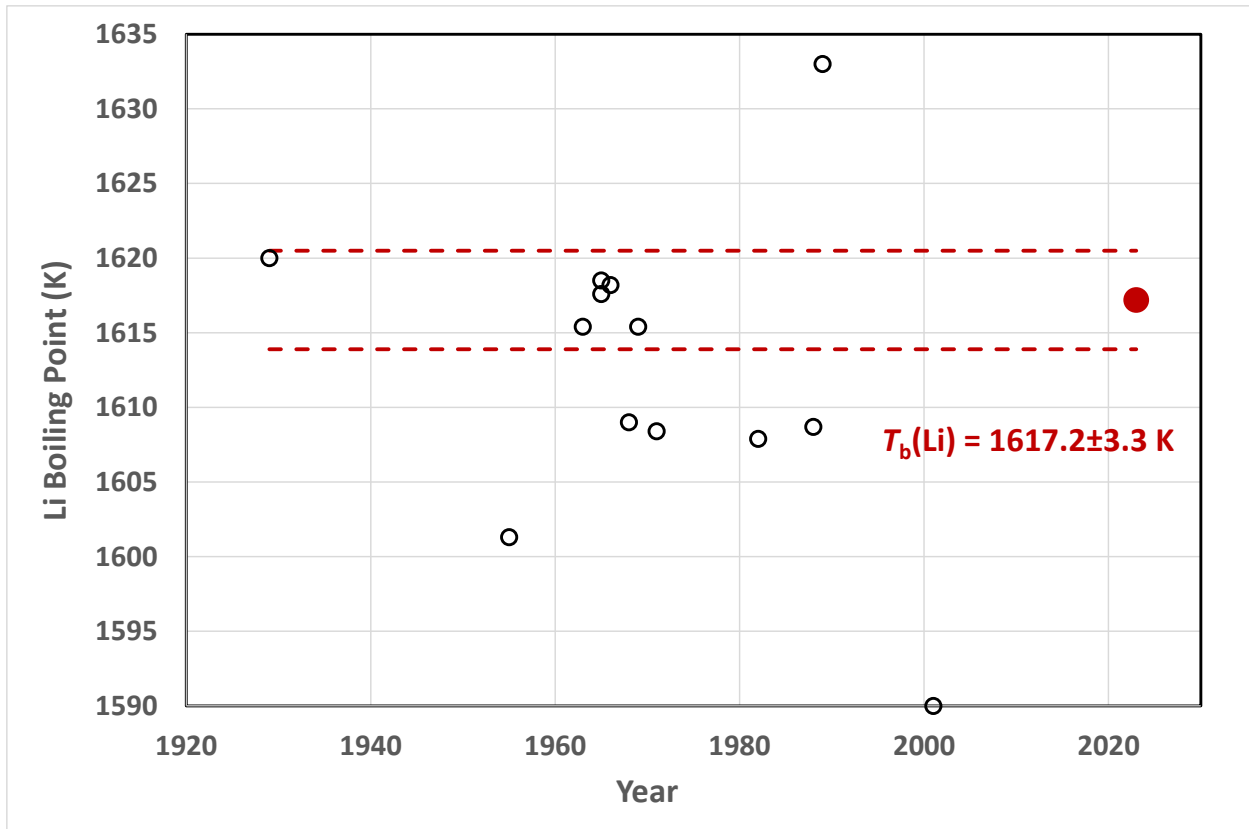


Figure 8. Boiling point values from Table 11 and recommendation for lithium from a fit to vapor pressure curves (see later table and figure). The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.

### 3.3. Alkali Metal Vapor Pressures and Enthalpies of Vaporization

Normal boiling points (1 atm = 1.01325 bar) can be computed from vapor pressure curves assuming the ideal gas law ( $PV=nRT$ ) using the Clausius-Clapeyron relationship:

$$\ln(P/\text{atm}) = A + B/T$$

and thus,

$$T_b = -B/A$$

Enthalpies of vaporization  $\Delta H_{\text{vap}}^{\circ}(T_b)$  at the normal boiling point can also be computed from vapor pressure curves assuming the ideal gas law:

$$\ln(P/P_o) = -\Delta H_{\text{vap}}/R \cdot (1/T - 1/T_o)$$

where  $R$  is the gas constant – thus, the slope of the  $\ln(P)$  vs  $1/T$  curve provides the enthalpy of vaporization (assuming the ideal gas law).

More accurate enthalpies of formation can be derived considering the compressibility of a real gas – how much the gas deviates from an ideal gas where a real gas includes a compressibility factor  $Z$ . Including a correction for nonideality reduces the derived enthalpies of vaporization. Employing the compressibility factor  $Z$  for a real gas, the gas law becomes

$$PV = Z \cdot nRT$$

and the enthalpy of vaporization of a real gas is

$$\Delta_v H = -Z \cdot RT \cdot \partial \ln(P) / \partial (1/T)$$

Table 12 provides the sets of vapor pressure curves that we considered. From a fit to selected data by Anisimov and Volyak (1969), [115] Bohdansk and Schin (1965), [31] and Rigney *et al.* (1965), [117], we determined an accurate boiling point for Li of  $1617.2 \pm 3.3$  K and an enthalpy of vaporization (ideal gas) for lithium of  $149.4 \pm 3.4$  kJ mol<sup>-1</sup>. In order to best determine the boiling point and enthalpy of vaporization, these data were fit near 1 atm: (0.77 to 1.18) atm and (1580 to 1640) K. The uncertainties in both  $T_b$  and  $\Delta_v H(\text{IG})$  were derived from the uncertainty in  $\ln(P)$  from the least-squares fit, which was  $U[\ln(P/\text{atm})] = 0.048$ . Using a compressibility factor  $Z = 0.854$  derived from the density of gaseous lithium taken from Vargaftik (1975) [53] at (1700, 1800, 1900, and 2000) K, we calculate the enthalpy of vaporization (real gas) to be  $127.6 \pm 6$  kJ mol<sup>-1</sup>. Here, we have estimated an uncertainty of 4 % in the compressibility factor.

Vapor pressures at (0.4 to 4400) mbar and (950 to 1860) K for lithium were taken from seven sets of data and then fit to determine a vapor pressure curve over the entire pressure range. The form of the fitting function of over this extended pressure was  $\ln(P) = a + b/T + c \cdot \ln(T)$ , where the parameters  $a$ ,  $b$ , and  $c$  given in Table 12. The individual pressure curves given in Table 12 were all fit near 1 atm using the simple form  $\ln(P) = A + B/T$  with temperatures corrected to the ITS-90 scale (not the original temperature scale) in order to derive a corrected boiling point and enthalpy of vaporization.

The deviations of the different vapor pressure measurements from the fit to these sets of data are provided in Figure 9 having an expanded uncertainty in  $P$  of 5.0 %.

**Table 12. Vapor Pressures of Lithium (Li) and Heats of Vaporization (ideal and real gas)**

$P(\text{Li})$	$T(\text{Li})/\text{K}$	$\ln(P(\text{Li})/\text{atm})$	$T_b(\text{Li})/\text{K}$	$\Delta_v H(\text{IG})/\text{kJ mol}^{-1}$	$\Delta_v H/\text{kJ mol}^{-1}$	Method	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>							
<b>0.78-1.19</b>	<b>1580-1640</b>	<b>11.118-17969/<math>T</math></b>	<b>1617.2<math>\pm</math>3.3</b>	<b>149.4<math>\pm</math>3.4</b>	<b>127.6<math>\pm</math>6</b>	<b>VP fits</b>	<b>Recommended</b>
0.1-1.3 bar	1057-1646	11.094-17921/ $T$	1615.4	149.0	127.2	VP fit	1969ANI [115]
0.4-3.4 bar	1178-2156	10.928-17577/ $T$	1608.5	146.1	124.8	VP fit	1968SHP [116]
0.1-4.9 bar	1374-1881	11.240-18192/ $T$	1618.5	151.2	129.2	VP fit	1965BOH [31]
0.1-7 bar	1273-1973	11.039-17856/ $T$	1617.6	148.5	126.8	VP fit	1965RIG [117]
<b>Other vapor pressure determinations</b>							
0.1-13 Pa	627-893	11.534-18339/ $T$	1590.0	152.5	130.2	VP fit	2001ZAI [119]
40-340 Pa	950-1070	10.932-17799/ $T$	1628.2	148.0	126.4	VP fit	1989ZOB [120]
0.1-1.8 bar	450-1700	11.410-18356/ $T$	1608.7	152.6	130.3	evaluation	1988WIL [114]
0.1-3.3 bar	1300-1800	11.531-18607/ $T$	1613.6	154.7	132.1	eval VP fit	1968DAV [125]
0.2-1 bar	1400-1600	11.623-18586/ $T$	1599.2	154.5	132.0	VP fit	1963HIC [33]
0.1-120 mbar	900-1350	11.483-18386/ $T$	1601.1	152.9	130.5	VP fit	1955DOU [27]
3-1050 mbar	700-1600	11.799-18787/ $T$	1592.3	156.2	133.4	eval VP fit	1941DIT [58]
20-110 mbar	1200-1350	11.188-18125/ $T$	1620.0	150.7	128.7	VP fit	1929HAR [118]
<b>Recommended vapor pressures over a wide range</b>							
<b><math>P = (0.001 \text{ to } 7300) \text{ mbar}</math> and <math>T = (730 \text{ to } 1970) \text{ K}</math></b>							
$\ln(P/\text{atm}) = 12.976 - 18302/T - 0.2239 \cdot \ln(T)$							
$U(P) = 5.0 \%$							
<b>Recommended vapor pressures near 1 atm</b>							
<b><math>P = (0.8 \text{ to } 1.2) \text{ bar}</math> and <math>T = (1580 \text{ to } 1640) \text{ K}</math></b>							
$\ln(P/\text{atm}) = 11.118 - 17969/T$							
$U(P) = 0.87 \%$							

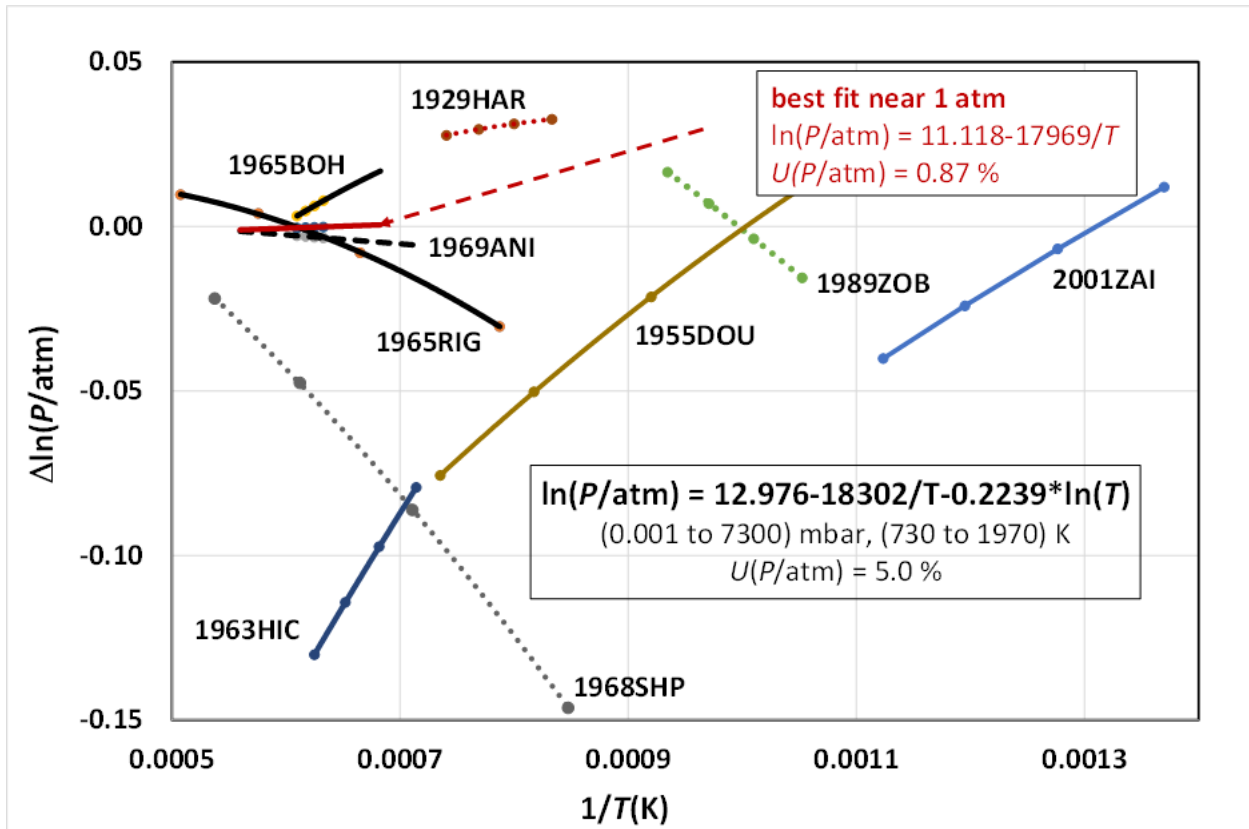


Figure 9. Deviation of Lithium Vapor Pressures from a Fit to  $\ln(P) = a + b/T + c \cdot \ln(T)$ ,



### 3.4. Sodium (Na) Boiling Point

There are quite a few determinations of the normal boiling point of Na with good-to-high precision (about 0.02 K to 0.2 K) ranging about (1155.5 to 1157.0) K. An unweighted average of all these values is about  $1156.2 \pm 1.0$  K, while considering only values  $< 3\sigma$ , the unweighted average is about  $1156.2 \pm 0.75$  K. The BIPM/CCT (Bureau International des Poids et Mesures/Consultative Committee for Thermometry) working group recommends a value of  $T_b = 1156.090 \pm 0.010$  K (see 1996BED[60]) with a very small uncertainty. This is based on a value of  $1156.09 \pm 0.02$  K from the 1992 report by Marcarino and Bassani,[130] who in a later publication Marcarino and Bonnier (2005)[131] gave a slightly lower value (0.05 K) of  $1156.04 \pm 0.02$  K. These values are slightly different to the value of  $1156.07 \pm 0.05$  K reported by Hill and Gotoh (1996)[132], who had a impurity level for potassium (K) of about 600 ppm. Hill and Gotoh also calculated that the boiling point determined by Marcarino and Bassani is likely depressed by about 0.012 K due to the presence of about 100 ppm potassium as an impurity. These sets of work provide very low uncertainties of 0.02 K, but when considering uncertainties due to both impurities and possible systematic errors, uncertainties on the order of 0.09 K may be more likely. We select the value from Marcarino and Bassani (1992) (also selected by BIPM/CCT), but assign a significantly higher uncertainty ( $1156.09 \pm 0.19$  K) (ignoring the estimated 0.012 K boiling point depression calculated by Hill and Gotoh) to reflect the range of reported boiling point values provided in Table 13.

Although there are many values in Table 13 and Figure 10 that are much lower than our recommended value those can possibly be discounted because of impurities, there are also other higher values that should be partially accounted for in determining an uncertainty. Some of the relatively reliable determinations include those by Bowles and Rosenblum (1965), Stone *et al.* (1966), Achener and Fisher (1967), Ewing *et al.* (1967), Vinogradov and Volyak (1966), and Bhise and Bonilla (1977), and many of these provide boiling points that are within (3 to 5) $\sigma$  of the recommended value.

In Table 13, we have corrected the values to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are -0.02 K and +0.88 K, respectively. In Figure 10, the recommended boiling point  $T_b = 1156.09 \pm 0.19$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are statistically identical to the recommended value. There are also a number of distinct outliers ( $> 4\sigma$ ) that differ by a large amount – many about (1 to 2) K, and some as much as (4 to 6) K from the recommended value.

**Table 13. Boiling Points of Sodium (Na)**

$T_b(\text{Na})/\text{K}$	$T_{90}/\text{K}$	$U(T_b)/\text{K}$	Method	Notes	Reference
<b>Considered values (&lt;3<math>\sigma</math>)</b>					
<b>1156.09</b>	<b>1156.09</b>	<b>0.19</b>	<b>Recommended</b>	<b>Selected 1992MAR</b>	<b>This work</b>
1156.04	1156.04	(0.09)	heat pipe		2005MAR [131]
1156.09	1156.09	(0.09)	heat pipe		2003REN [133]
1156.07	1156.07	(0.09)	heat pipe		1996HIL [132]
1156.090	1156.090	0.020	evaluation	selected 1992MAR	1996BED [60]
1156.09	1156.09	(0.09)	heat pipe		1992MAR [130]
1155.2	1156.2		pressure tube		1977BHI [134]
1155.12	1155.10		evaluation, heat pipe		1971SCH [122]
1155.98	1155.96		evaluation VP	1.0 bar	1969HON [135]
1156	1157	na	VP		1967BOH [136]
1155.5	1156.5		VP		1967ACH [137]
1156.0	1156.9	0.3	VP	1-1000 mbar	1966VIN [19]
1156.07	1156.95	0.05	VP	0.9-1.6 bar	1966STO [123]
1154.6	1155.5	4.3	VP	quoted in 1985OHS	1966STO [123]
1154.4	1155.4		VP	0.01-0.5 bar	1966FIS [138]
1155.5	1156.5	0.3	VP	0.9-5.0 bar	1966EWI [139]
1154.59	1155.47	0.5	VP	0.5-120 bar	1965BOW [140]
1156	1157	na		quoted in 1985OHS	1963SOW [141]
1154.52	1155.40		VP		1962BON [142]
1154.4	1155.3	4.7	VP		1955MAK [143]
1155	1156	na			1950INA [144]
1156	1157	na		quoted in 1985OHS	1930LAD [69]
1156	1157	0.2	VP		1925ROD [145]
1156.1	1157.0		thermal		1912HEY [146]
<b>Other values</b>					
1156.2	1156.2	0.27	sel unweighted avg		This work
1156.1	1156.1	1.2	unweighted average		This work
1156.34	1156.34	na	EOS	0.2-3.2 bar	2018ZHA [147]
1154.6	1154.6		VP		1977GUP [148]
1154.0	1154.0	3.6	VP		1971SCH [122]
1150.15	1151.03		VP	quoted in 1985OHS	1965ACH [149]
1158.4	1159.3	2.7	VP	1.2-3.4 bar	1959KIR [150]
1153	1154		VP		1931LEW [151]
1161.2	1162.1		VP	0.065-0.66 bar	1930ROD [152]
1156.2	1157.1	na	VP	0.4-40 Pa	1930ROD [153]
1152.9	1153.8	na	VP	0.05-2 Pa	1927EDM [70]
1143.3	1144.2	na	VP	0.001-1 bar	1925ROD [145]
1134	1135	na	VP		1923MIL [154]
1150.7	1151.6	5	thermal analysis		1905RUF [155]
<b>Reviews and evaluations</b>					
1156.09	1156.09		review		2020RUM [50]
1154.55	1154.55		evaluation		2006VEL [124]
1154.5	1154.5	1.0	evaluation		1985OHS [29]
1151.3	1151.2		review VP	0.1-4.6 bar	1975VAR [53]
1156	1156		evaluation		1973HUL [55]
1154.7	1154.7		evaluation		1970SHP [56]

1155.9	1156.9	na	evaluation VP		1963HIC [33]
1154	1155	na	evaluation VP		1941DIT [58]
1162	1163	na	evaluation VP		1936GOR [126]
<b>To abstract</b>					
-					1996FIN [156]
-					1969HON [157]
-					1966STO [158]
-					1966EWI1 [139]
-					1966DIL [159]
-					1934FIS [160]
-					1934BAU [161]
-					1932THI [162]
-					1927ROW [163]
-					1921LAD [164]
-					1913KRO [165]
-					2017VAZ [166]
-					1980ERE [167]
-					1926POI [168]
-					1927BEN [169]
-					1967VIN [170]

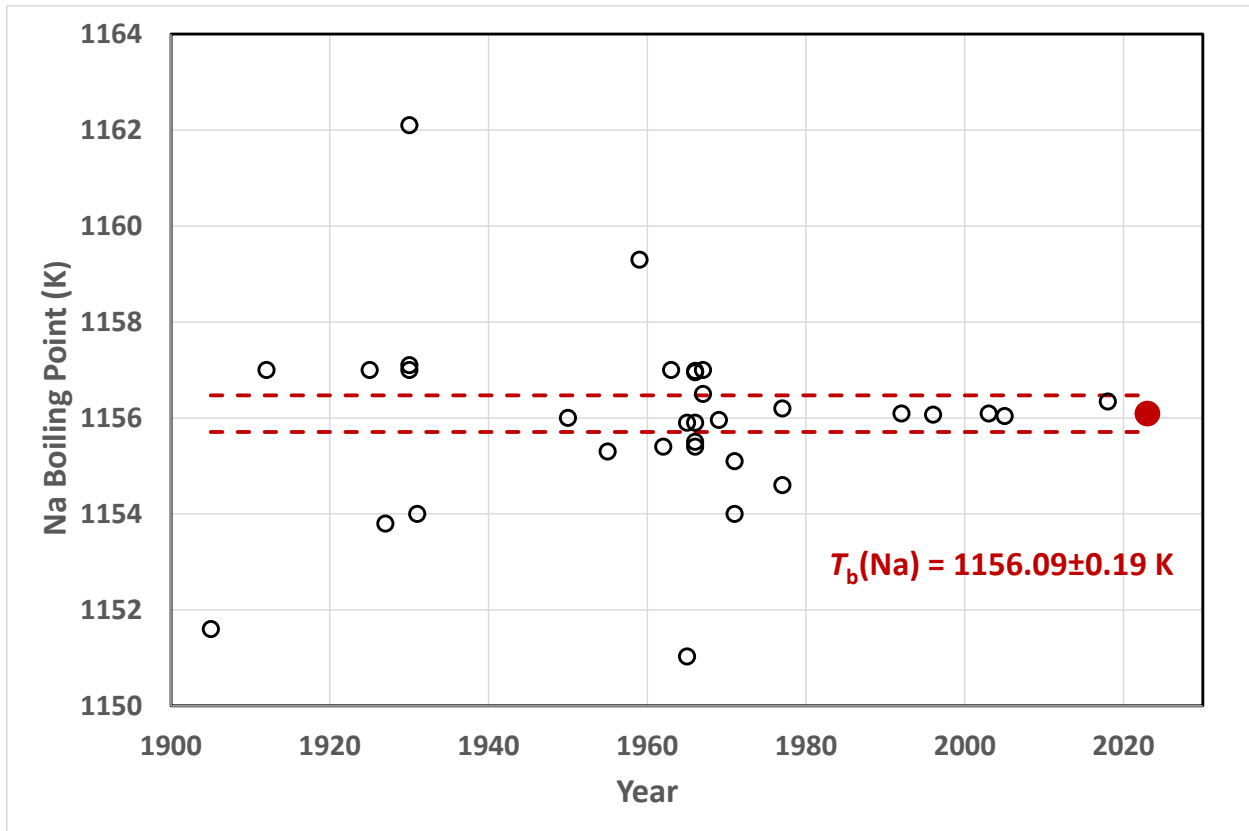


Figure 10. Boiling point values for sodium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.

### 3.5. Potassium (K) Boiling Point

There are many determinations of the normal boiling point of potassium, however, there are some disparities (by several degrees) in the values. The data is provided in Table 14 and Figure 11. The values range from about 1030 K to about 1035 K with an unweighted average of about  $1032 \pm 2.9$  K. Considering only the most reliable values, they range about from about 1030 K to 1032 K with an unweighted average of about  $1031.0 \pm 1.9$  K. We select the value from the work of Renaot *et al.* (2003) of  $T_b = 1031.45 \pm 0.7$  K and assign a much higher uncertainty than reported (0.022 K) to account for the spread in other values. In Table 14, we have corrected the reported boiling points to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are +0.04 K and +0.59 K, respectively.

In Figure 11, the recommended boiling point  $T_b = 1031.45 \pm 0.7$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $3\sigma$  uncertainty ( $2\sigma = 0.7$  K). There are a fair number of values that are statistically identical to the recommended value. There are also a number of distinct outliers ( $>4\sigma$ ) – some differing (3 to 4) K from the recommended value.

**Table 14. Boiling Points of Potassium (K)**

$T_b(K)/K$	$T_{90}/K$	$U(T_b)/K$	Method	Notes	Reference
<b>Considered values (&lt;3<math>\sigma</math>)</b>					
<b>1031.45</b>	<b>1031.45</b>	<b>0.7</b>	<b>Recommended</b>	<b>Selected 2003REN</b>	<b>This work</b>
1031.45	1031.45	0.022	heat pipe	870-1110 K; 0.2-2 bar 13.062-10301/ $T-0.443*\ln(T)$ 9.5444-9845/ $T$ ; $\Delta_vH=81.9$ kJ/mol	2003REN [133]
1033.06	1033.10	na	heat pipe	quoted in 1985OHS	1971SCH [122]
1029.3	1029.3	1.2	BP	quoted in 1985OHS	1972SHP [171]
1029.39	1029.98		BP	quoted in 1985OHS	1968SHP [116]
1030.3	1030.9			945-2170 K; 0.4-130 bar; 17.842-11081/ $T-1.022*\ln(T)$ ; $\Delta_vH=83.4$ kJ/mol	1968BOW [172]
1029.97	1030.56	0.16	VP		1966STO [123]
1029.8	1030.4	(0.7)		1033-1644 K; 1-34 bar; 12.893-10256/ $T-0.422*\ln(T)$ ; $\Delta_vH=81.6$ (1.0) kJ/mol	1966EWI2 [30]
1031	1032	na	VP		1963HIC [33]
1030.15	1030.74		VP	at 1.04 bar	1926FIO [173]
1030.4	1031.0		VP	0.006-1.01 bar	1926FIO [173]
1030.5	1031.1		thermal anal	quoted in 1985OHS	1905RUF [155]
<b>Other values</b>					
1031.0	1031.0	1.9	sel unweighted avg		This work
1031.53	1031.53		EOS	0.2-3.8 bar	2018ZHA [147]
1034.0	1034.6		VP	quoted in 1985OHS	1966VIN [19]
1034	1035		BP	quoted in 1985OHS	1963WAL [174]
1034.6	1035.2	na	VP		1963WAL [174]
1069.3	1069.9		VP	distinct outlier	1960GRA [94]
1027.0	1027.6	na	VP	distinct outlier	1956MAK [175]
967	968		VP	distinct outlier	1926KIL [176]
<b>Recommendations and evaluations</b>					
1032.15	1032.15		evaluation		2020RUM [50]
1029.83	1029.83	na	evaluation		2006VEL [124]
1031	1031	1.0	evaluation		1985OHS [29]
1029.9	1029.9		evaluation		1981GOG [177]
1031.5	1031.4		review VP	0.1-3.9 bar	1975VAR [53]
1032	1032		review		1973HUL [55]
1029.9	1029.9		review		1970SHP [56]
1033	1034	na	evaluation VP		1941DIT [58]
<b>To abstract</b>					
-					1978MIK [178]
-					1969HON [157]
-					1966STO [158]
-					1966DIL [159]
-					1965RIG [179]
-					1963LEM [180]
-					1934FIS [160]
-					1931MAY [181]

-					1929WEI [182]
-					1927ROW [163]
-					1980BEL [183]
-					1972FRE [184]
-					1926POI [168]
-					1961THO [185]
-					1967VIN [170]
-					1968SHP [186]

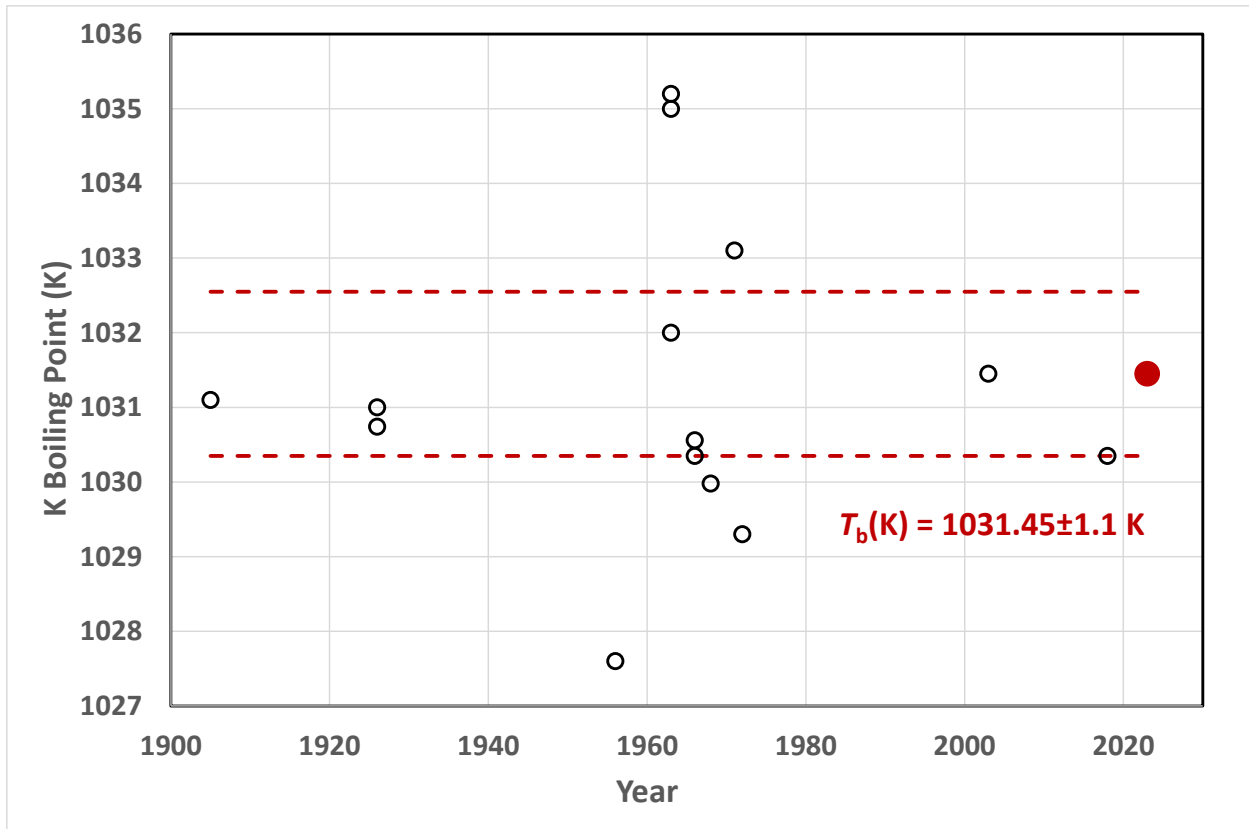


Figure 11. Boiling point values for potassium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.



### 3.6. Rubidium (Rb) Boiling Point

There are only a few determinations for the normal boiling point of Rb and they have relatively poor precision (about 1 K to 5 K). Excluding the slightly high value ( $\approx 4s$ ) from Achener (1964)[187], we calculate an average of about  $T_b = 960 \pm 2$  K. We have corrected the values in Table 15 to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are  $-0.04$  K and  $+0.31$  K, respectively.

In Figure 12, the recommended boiling point  $T_b = 960 \pm 2$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are statistically identical to the recommended value.

Table 15. Boiling Points of Rubidium (Rb)

$T_b(\text{Rb})/\text{K}$	$T_{90}/\text{K}$	$U(T_b)/\text{K}$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
<b>960</b>	<b>960</b>	<b>2</b>	<b>Recommended</b>	<b>Unweighted average</b>	<b>This work</b>
958	958		BP	quoted in 1985OHS	1972SHP [171]
960.1	960.1		VP	956-1922 K; 1-100 bar; 12.109-9292/ $T-0.354*\ln(T)$ ; $\Delta_v H=74.3$ kJ/mol	1972CHE [188]
960.0	960.0	3.0	heat pipe	quoted in 1985OHS	1971SCH [122]
962	962	na	VP		1967BOH [136]
963.37	963.68	na	VP		1964ACH [187]
958.7	959.0	na	VP		1963WEA [38]
958.88	959.29		VP	quoted in 1985OHS	1962BON [142]
<b>Other values</b>					
976.62	976.62		EOS	0.1-5.5 bar	2018ZHA [147]
969	969	5.0	thermal analysis	quoted in 1985OHS	1905RUF [155]
<b>Reviews and evaluations</b>					
960	960	1.0	evaluation		1985OHS [29]
958	958		evaluation		1981GOG[177]
959.9	959.8	(1.5)	review VP	0.2-4.7 bar	1975VAR [53]
<b>To abstract</b>					
–			fluorescence	297- 334 K; reports $N$ -density, not $P$	2015ZHA [189]
–			fluorescence	250-298 K; 0.1-100 $\mu\text{Pa}$ ; 17.20-22244/ $T-0.0050*\ln(T)$ ; $\Delta_v H=82.3(0.3)$ ; TW 84.7(2.0) kJ/mol	1988VAN [190]
957		(5-7)		536-874 K; 53-40000 Pa; 9.553-9142/ $T$ ; $U(P)=3\%$ ; $\Delta_v H=76.0(1.4-3.4)$ kJ/mol	1986KAL [191]
–				400-520 K	1982THO [192]
–			VP,TGA,MS	400-500 K	1973PIA [193]
–			absorb	326-339 K; reports density, not $P$ ; $\Delta_v H=78.5$ kJ/mol	1973GAL [194]
966.8	0.5			675-1500 K; 17-17000 torr; 9.807-8580/ $T-0.136*\ln(T)$ ; $U(P)=2\%$ ;	1971SHP [195]

				$\Delta_v H = 70.2(2.0)$ kJ/mol;	
-					1969HON [157]
-				594-925 K; 0.04-7.4 atm; 960.1(0.3/1.1) K; 15.017-9636/T-0.725*ln(T) 74.4(0.7) kJ/mol;	1968VOL [196]
-					1967STO [197]
-					1967HUL [198]
-					1966GRO [199]
-					1966DIL [159]
-					1959KIR [150]
-					1941DIT [58]
-					1927ROW [163]
-					1926KIL [176]
-					1924SCO [200]
-					1913KRO [165]
-					1913HAC [201]

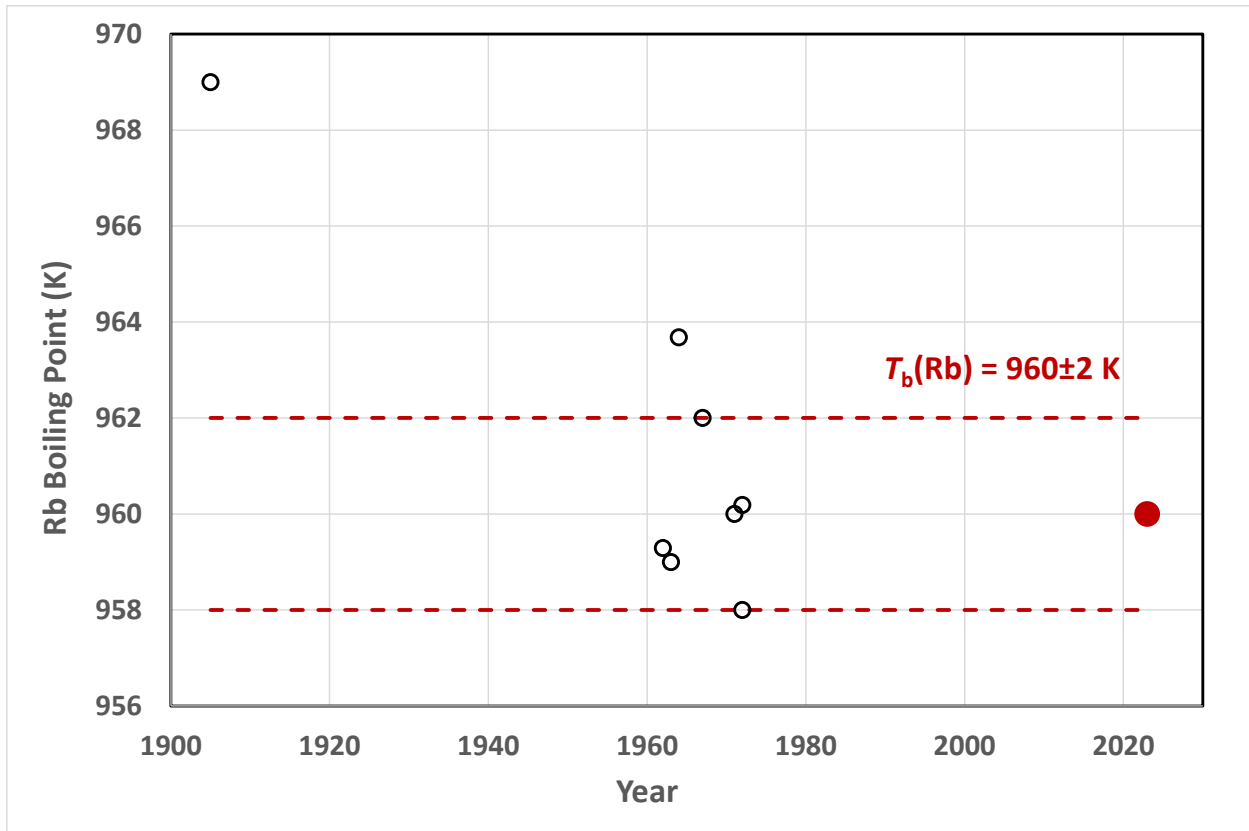


Figure 12. Boiling point values for rubidium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.

### 3.7. Cesium (Cs) Boiling Point

There are many determinations of the normal boiling point of cesium with a wide range of values from about 938 K to 945 K. We select a value of  $941.4 \pm 0.5$  K derived from the vapor pressure measurements of Cherneeva and Proskurin (1972)[202] and observe that most of the reported values are within (2 to 3)% of this value (including an unweighted average of  $941.7 \pm 1.1$  K). A more accurate value could be obtained by fitting the sets of vapor pressure curves reported for the different sets of measurements (this, however, was not done in this work). We have corrected the values in Table 15 to the ITS-90 temperature scale – the  $\delta T_{68}$  and  $\delta T_{48}$  corrections are -0.07 K and +0.24 K, respectively. In the “Notes” column, we provide an expression for the vapor pressure in the form  $\ln(P/\text{atm}) = A + B/T$  from fits near 1 atm and the corresponding heat of vaporization  $\Delta_v H$ . Note that the temperatures in these expressions were not corrected to the ITS-90 scale, and should be if they are employed to determine a more accurate boiling point from a fit to set of vapor pressure curves. The boiling points, however, were corrected to the ITS-90 scale.

In Figure 13, the recommended boiling point  $T_b = 941.4 \pm 0.5$  K is given as a large, filled circle, while the other values are displayed as smaller, open circles. The dotted lines reflect a  $2\sigma$  uncertainty. There are a fair number of values that are statistically identical to the recommended value. Additionally, there are several values that differ by as much as 3 K from the recommended value.

**Table 15. Boiling Points of Cesium (Cs)**

$T_b(\text{Cs})/\text{K}$	$T_{90}/\text{K}$	$U(T_b)/\text{K}$	Method	Notes	Reference
<b>Considered values (<math>&lt;3\sigma</math>)</b>					
941.4	941.4	0.5	Recommended	Selected 1972CHE	This work
942.9	942.9	(1.0)	VP fit	0.1-0.93 bar; 9.0055-8491.2/T; $\Delta_v H=70.6$ kJ/mol	1996HIL [203]
942.02	941.95		VP		1972SHP [171]
941.6	941.6			1028-1873 K; 0.8-80 atm; 13.150-8990/T-0.526*ln(T); $\Delta_v H=70.1$ kJ/mol	1972CHE [188]
941.5	941.4		VP		1972CHE [202]
940.7	940.6		VP		1970SHP [56]
941.7	941.9		VP		1967SHP [204]
942	942		VP		1966STO [205]
940.6	940.8		VP fit	quoted in 1966EWI	1966STO [205]
942.40	942.64	0.61	VP	0.03-11 bar	1966STO [123]
942.1		(0.4)		1300-2300 K; 1.4-30 atm; 13.222-9008/T -0.534*ln(T); $\Delta_v H=70.3(0.2)$ kJ/mol	1966EWI3 [206]
942.04	942.28		PVT		1966EWI [207]
940.6	940.8		VP fit	1.9-41 mbar; 8.8861-8358/T; $\Delta_v H=69.5$ kJ/mol	1966EWI [207]
<b>Other values</b>					
941.7	941.7	1.1	unweighted average		This work
938.3	938.2	3.1	heat pipe		1971SCH [122]
939	939		VP		1967BOH [136]
938.1	938.3	3	VP fit	53-4880 mbar; 9.0662-8505/T; $\Delta_v H=70.7$ kJ/mol	1965BOH [31]
944.87	945.12	na	VP		1964ACH [187]
977.1	977.3	2.4	VP fit	0.3-1220 mbar; 8.1779-7991/T; $\Delta_v H=66.4$ kJ/mol	1937TAY [104]
943	943	5	thermal analysis		1905RUF [155]
<b>Reviews and evaluations</b>					
944.15	944.15		review		2020RUM [50]
942.05	942.05		evaluation		2006VEL [124]
940.7	940.7		evaluation		1981GOG [177]
941.5	941.5	1	evaluation		1985OHS [29]
942.6	942.5	(1.0)	review VP	0.2-5.0 bar; 8.9737-8459.2/T; $\Delta_v H=70.3$ kJ/mol	1975VAR [53]
944	944		review		1973HUL [55]
1033	1033		evaluation	VP fit	1941DIT [58]
<b>To Abstract</b>					
-					1990KOZ [208]
-					1977BEH [209]

-					1972CHE [188]
-					1971EWI [210]
-					1969HON [157]
-					1966STO [158]
-					1966GRO [199]
-					1966EWI3 [207]
-					1966DIL [159]
-					1936LIE [211]
-					1933BOE [212]
-					1927ROW [163]
-					1924SCO [200]
-					1913KRO [165]
					1975GUS [213]
					1974PRA [214]
					1927BEN [169]
					1965ROZ [215]
					1971VET [216]

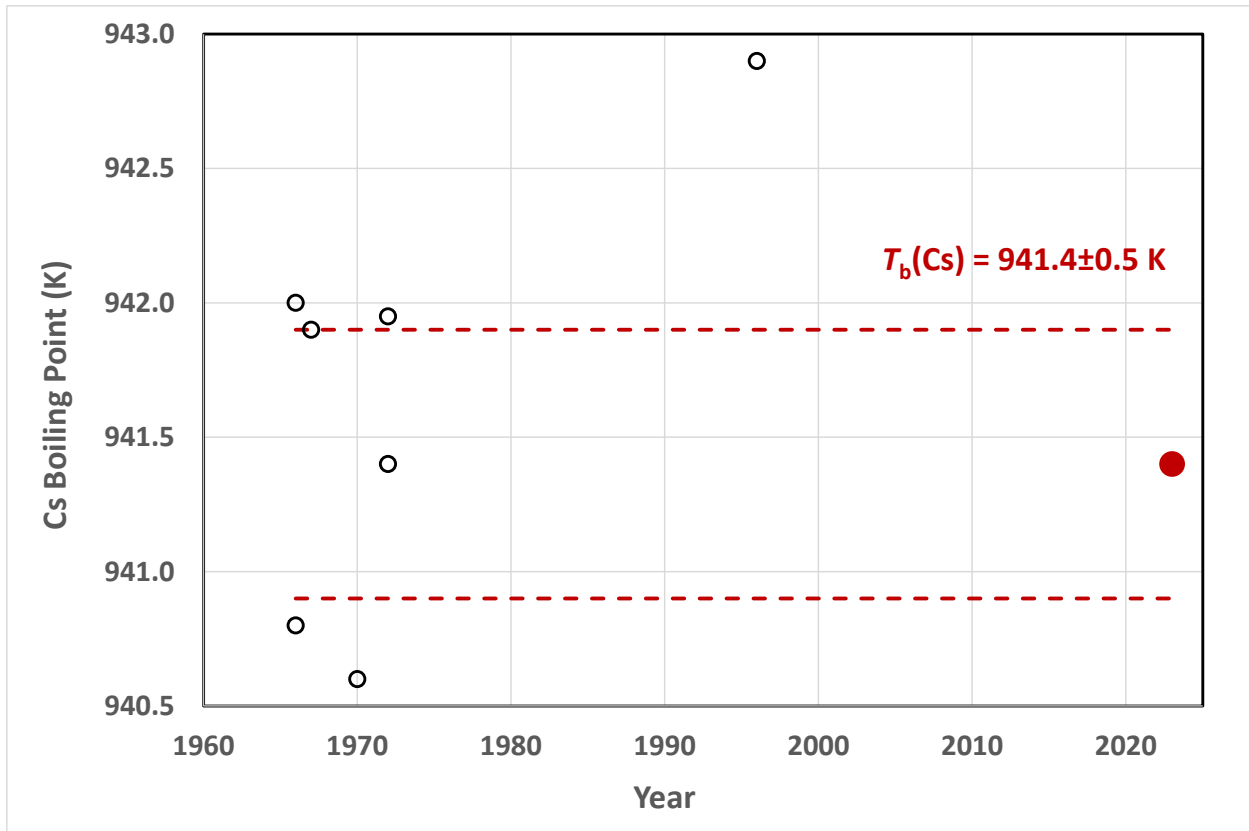


Figure 13. Boiling point values for cesium. The solid point is the recommended value, and the dotted lines indicate the expanded uncertainty.

### 3.8. Francium (Fr) Boiling Point

Various estimated values for the boiling point of francium can be found in the literature,[108] [109] [110] [111] [177] [217] [218] [219] mainly from Russian journals, and on the internet, ranging from about 923 K to 953 K – the most often quoted value is 950 K. All estimates are based on trends in boiling points of the other alkali metals. The boiling point must be estimated, because francium has no stable isotopes and cannot be isolated. Based on decreasing successive differences in the boiling points of the alkali metals, we estimate that the boiling point of francium is about 942 K (1 K higher than that for cesium). Based on trends in melting points with Van der Waals and covalent radii,[50] we estimate that the boiling point for francium to be 938.4 K and 933.0 K, respectively. Consequently, we adopt an average of these two latter values  $T_b = 936 \pm 6$  K (5 K lower than that for cesium).

**Table 13. Boiling Points of Francium (Fr)**

$T_b(\text{Fr})/\text{K}$	$T_{90}/\text{K}$	$U(T_b)/\text{K}$	Method	Notes	Reference
936	936	6	Recommended	Est from radii corr	This work
<b>To Abstract</b>					
–					2023WIK [111]
–					2023PUB [110]
–					2011LNL [109]
–					2003KOZ [219]
–					1998EMS [108]
–					1981GOG [177]
–					1979GLA [218]
–					1969OSM [217]
–					1969HON [157]



#### 4. Summary

In this work, we compiled, evaluated, and selected recommended values for use for the normal melting points ( $T_m$ ) and normal boiling points ( $T_b$ ) of the alkali metals: lithium (Li), sodium (Na), potassium (K), rubidium (Rb), cesium (Cs), and francium (Fr). We provide all of the measurements in the literature for melting points and boiling points of these elements along with selected recommended values. We also compiled and evaluated vapor pressures for lithium from the literature and fitted these sets of data in order to more accurately determine the boiling point. From these fits, we computed an enthalpy of vaporization  $\Delta_v H(\text{IG})$  assuming the ideal gas law and then employed a compressibility factor  $Z$  to compute the real gas enthalpy of vaporization  $\Delta_v H$ . In future work, we will evaluate sets of vapor pressure curves and derive more accurate values for the boiling points and determine enthalpies of vaporization for the other alkali metals Na, K, Rb, and Cs. For all of the values reported prior to 1990, we corrected the values to the International Temperature Scale of 1990 (ITS-90).[1] [2] [3]

### **Declaration of Competing Interest**

The authors have no conflicts to disclose.

### **Data Availability**

The data that support the findings of this study are available within the article.

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