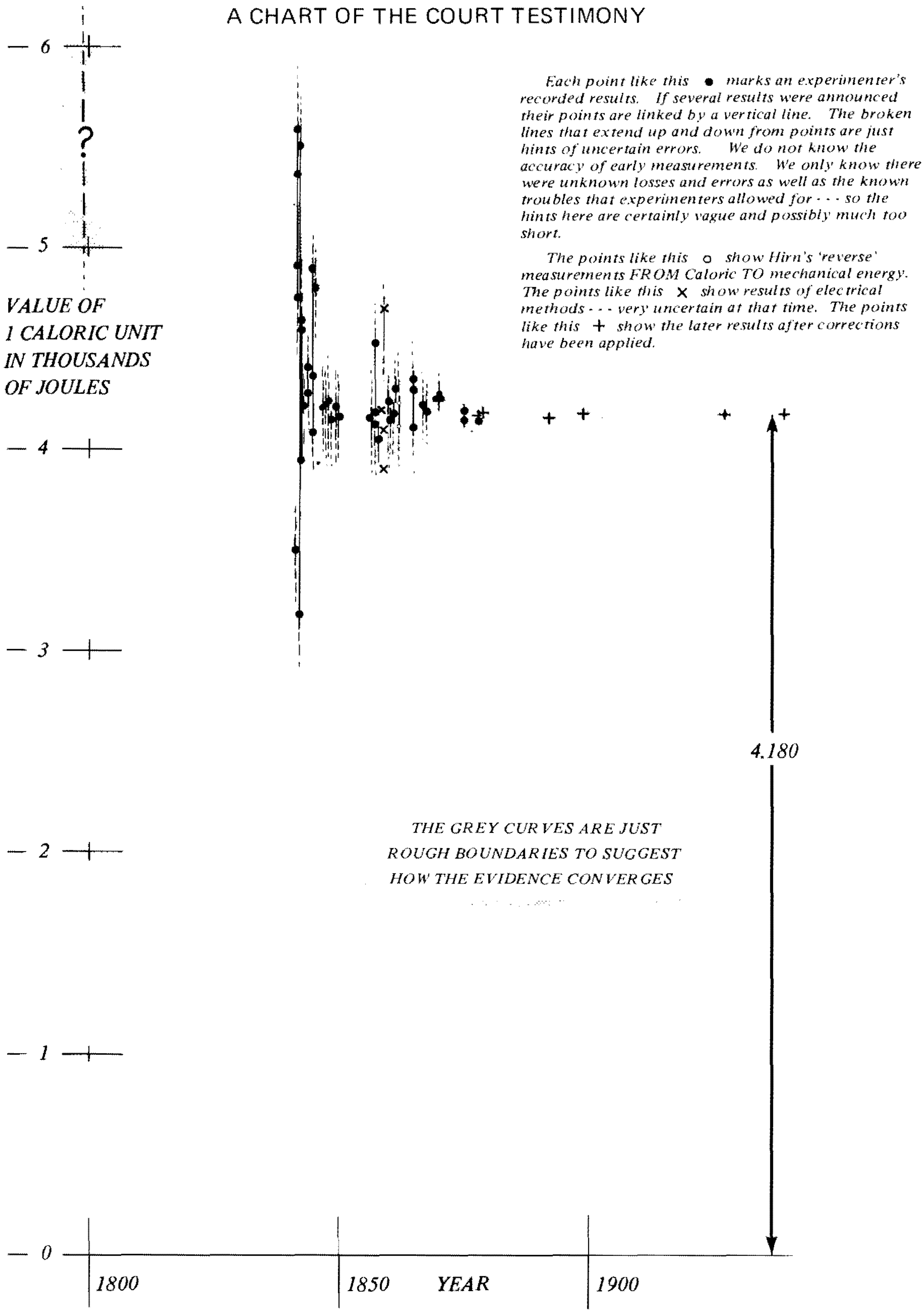
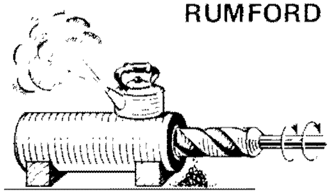
A CHART OF THE COURT TESTIMONY



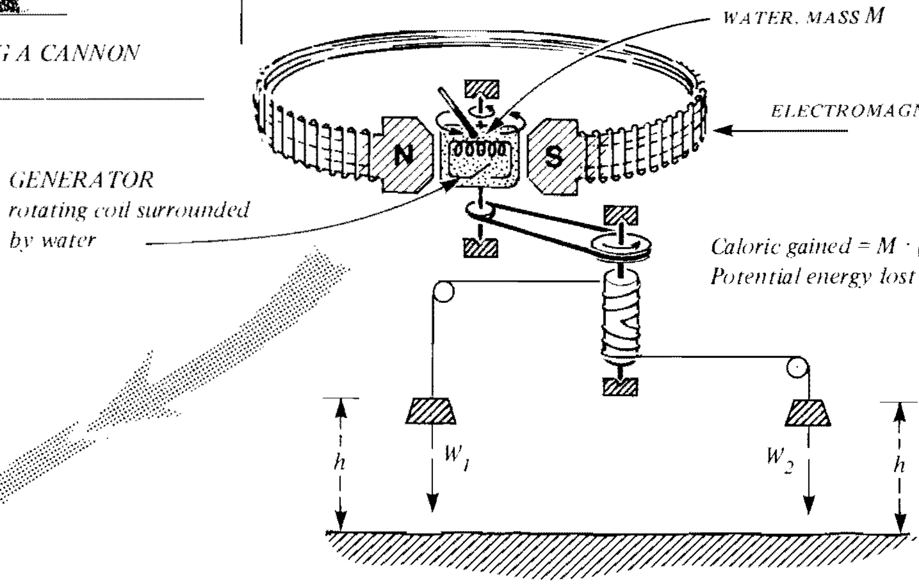
RUMFORD



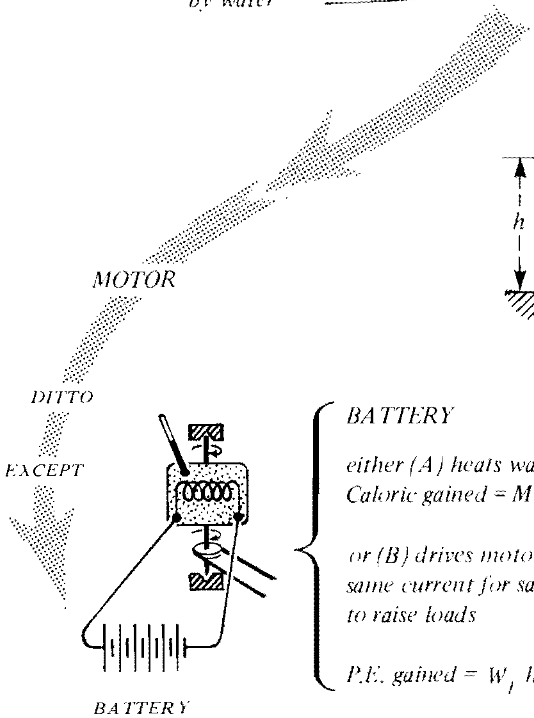
BORING A CANNON

JOULE

ELECTROMAGNETIC MACHINE



Caloric gained = M · (temp. rise)
Potential energy lost = $W_1\ h + W'_2\ h$



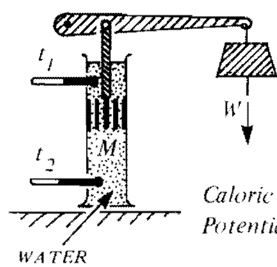
BATTERY

either (A) heats water
Caloric gained = M · (temp. rise)

or (B) drives motor with the same current for same time to raise loads

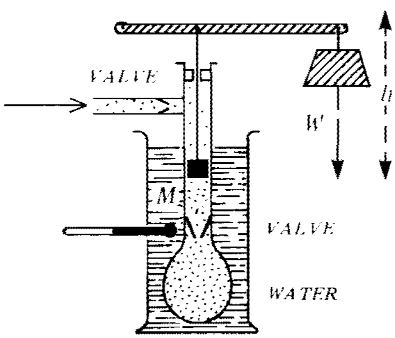
P.E. gained = $W_1\ h + W_2\ h$

PISTON WITH HOLES



Caloric gained = $M \cdot (t_1 - t_2)$
Potential energy lost = W · h

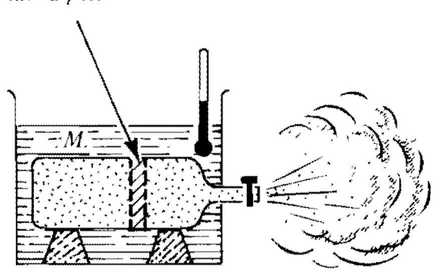
COMPRESSING AIR



Potential energy lost = W · h
Caloric gained = M · (temp. rise)

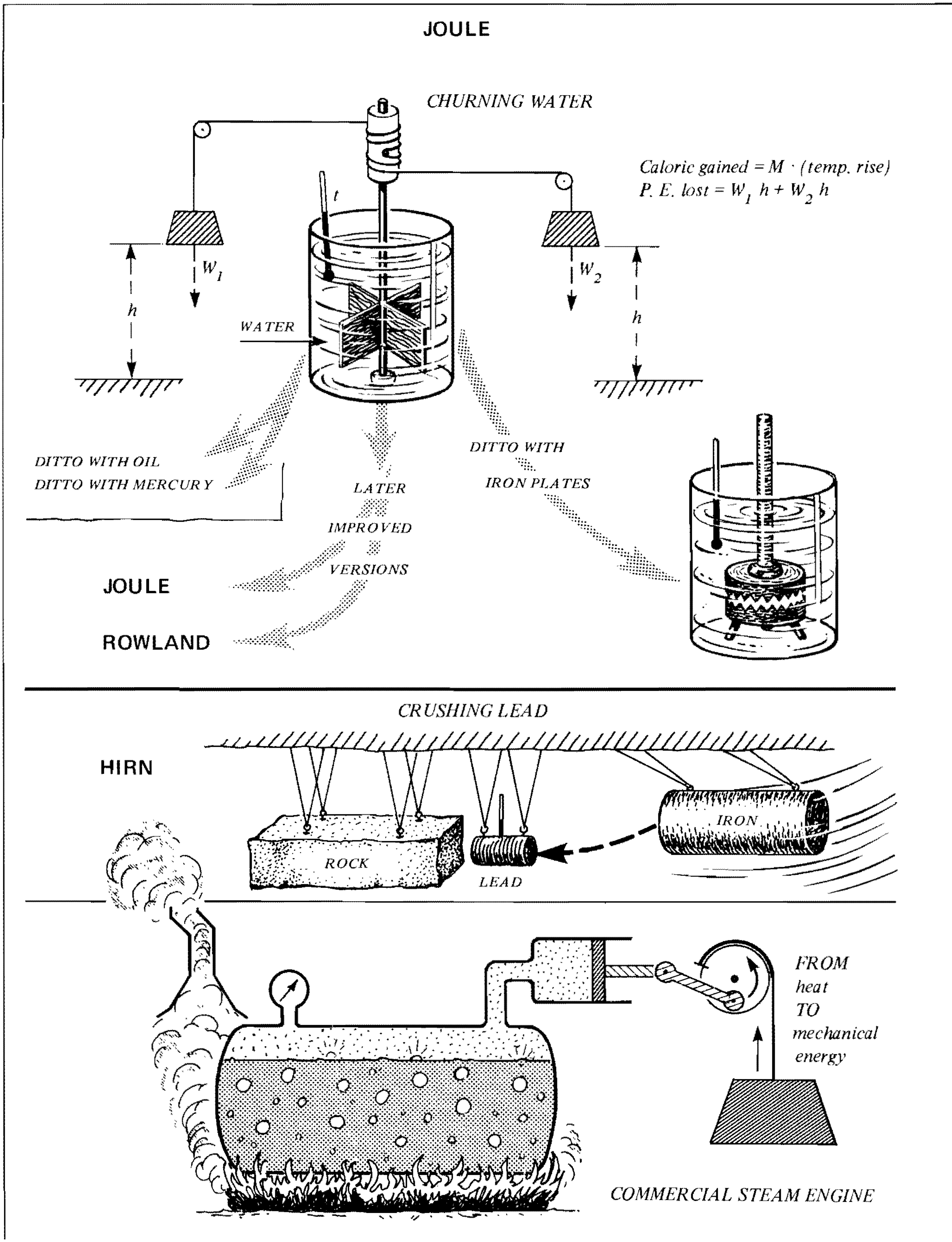
AIR EXPANDS AND COOLS

Atmosphere pushed away, acts like a piston



Caloric lost by water = M · (temp. fall)
Mechanical energy supplied by molecules of expanding air
= (pressure) · (increase of volume)

DATE	EXPERIMENTER	METHOD	RESULT *Value of 1 Caloric Unit in thousands of joules*
1798	RUMFORD	Cannon boring with blunt tool. Horse driving boring machine produced "endless supply" of heat. [Rumford made no estimate of mechanical equivalent, but guesses based on his record of horse's work and water heating led, according to Joule, later, to a rough value.]	5 or 6
1842	MAYER	Suggested the name, 'MECHANICAL EQUIVALENT OF HEAT'. Made an estimate from specific heat capacities of gases, using rough data, making serious assumptions.	3.5
1839–1843	JOULE	Experimented with electric currents, and wrote reports that showed he was interpreting heating effects and chemical effects in terms of his growing belief in something like energy-conservation, with heat a form of motion.	
1843	JOULE	Built simple electric machine which could be used as a generator or as a motor. Drove it as dynamo by falling weights; measured caloric produced when dynamo drove a current through coil immersed in water. (Coil was actually the rotating armature-coil of the machine.) Subtracted results of experiments with magnet turned off ("light run") from those with magnet on ("heavy"), to get rid of friction of bearings, etc.	4.76 5.38 5.60 4.90
1843	JOULE	Same electric machine used as a motor: (A) Battery drove motor, which raised weights: *or* (B) The same battery sent same current for the same time through a wire and heated it. [Actual arrangement was more indirect, but essentially like this.]	5.51 3.15
		ditto, improved apparatus.	4.62, 4.62, 3.95
1843	JOULE	Water, driven through fine tubes, was warmed up by fluid friction. (Piston with very fine holes drilled through it was pushed by measured force through water in a cylinder.)	4.22
1844	JOULE	Air, compressed by many successive strokes of piston-pump, warmed up. The compressed-air bottle was surrounded by large mass of water to remove and measure the caloric developed. In calculating mechanical energy used, Joule used Boyle's Law to allow for changes of compressing force.	4.42
1845	JOULE	ditto, greater compression.	4.27
1845	JOULE	Compressed air, from bottle in a water bath, expanded, pushing away the atmosphere (as a piston) and thus cooled.	4.08, 4.37, 4.91
1845	JOULE	Paddle-wheel, driven by falling weights, churned water and heated it by fluid friction. [The first form of Joule's great experiment.]	4.80
1847	JOULE	Improved paddle-wheel churned water. [Joule wound up the weights and let them fall again 20 times, to obtain enough temperature rise. He allowed for the caloric lost meanwhile to the air, etc. He allowed for K.E. which the weights had when they hit the floor.]	4.21
		ditto, churning *whale oil* instead of water [used known specific heat capacity of oil].	4.22
		ditto, churning *mercury*.	4.24



JOULE
CHURNING WATER
Caloric gained = M · (temp. rise)
P. E. lost = W_1 h + W_2 h
t
W_1
W_2
h
h
WATER
DITTO WITH OIL
DITTO WITH MERCURY
LATER
IMPROVED
VERSIONS
DITTO WITH
IRON PLATES
JOULE
ROWLAND
CRUSHING LEAD
HIRN
ROCK
LEAD
IRON
FROM
heat
TO
mechanical
energy
COMMERCIAL STEAM ENGINE

DATE	EXPERIMENTER	METHOD	RESULT *Value of 1 Caloric Unit in thousands of joules*
1848	JOULE	ditto, churning *water*. Forty more experiments with greater care. [Joule believed this result reliable to 0.5%.]	4.15
1850	JOULE	ditto, churning *mercury*.	4.16
1850	JOULE	Friction of *iron plates* rubbed together.	4.21
1857	FAVRE	Battery produced: (A) mechanical energy; *or* (B) caloric, for same current and time.	4.17 to 4.54
1857	HIRN	Bored metal with blunt borer.	4.16
1861	HIRN	Drove a water-cooled metal brake.	4.23
	HIRN	Liquid warmed up when driven through hole by high pressure.	4.16
	HIRN	Crushed a lead block. A 320-kilogram hammer moving 4.5 metres/second smashed a 3-kilogram block of lead against a 1000-kilogram anvil of stone. The lead warmed up about 5°C.	4.17
	HIRN	Compressed air expanded and cooled as it pushed against the atmosphere.	4.31
	HIRN	Steam engine (FROM caloric TO MECHANICAL ENERGY). Borrowed the use of a steam engine in a commercial mill; estimated total caloric given to steam by furnace; allowed for unmeasured caloric wasted by radiation, given to condenser, etc.; estimated mechanical energy delivered in hauling up a load.	4.12 to 4.23
1858	FAVRE	Friction of metals in mercury.	4.05
1857	QUINTUS ICILIUS	Indirect electrical methods. Measured: (A) caloric produced by	3.9
	WEBER	current in a wire; (B) caloric produced in beaker of same battery-	4.2
	FAVRE	chemicals.	4.2
to	SILBERMAN	Estimated mechanical energy indirectly by electrical instru-	4.2
	JOULE	ments: absolute ammeter, voltmeter, and/or ohm.	4.1
	BOSCHA	(The electrical units were still uncertain, so the results were not	4.1
1859	LENZ & WEBER	reliable.)	3.9 to 4.7
1865	EDLUND	Expansion and contraction of metals.	4.35, 4.21, 4.30
1867	JOULE	Caloric produced by known electric current through known resistance.	4.22
	WEBER	ditto	4.21
1870	VIOLLE	Disc rotated in magnetic field was heated by electrical 'eddy currents'. Measured mechanical drag and caloric output—no electrical measurements.	4.26 4.26 4.27
1875	PULUJ	Friction of metals.	4.167 to 4.180
1878	JOULE	Water churned by paddle: improved apparatus [weighted average of 34 experiments].	4.158(5)

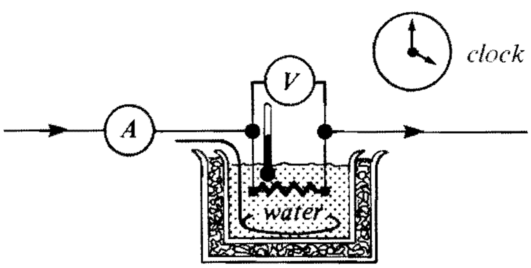
DATE	EXPERIMENTER	METHOD	RESULT *Value of 1 Caloric Unit in thousands of joules*

By then, the case was proved, and the remaining question was the exact length of sentence. The value of the mechanical equivalent, J was being measured so accurately that a careful measurement of g had to be used; and the value of 1 caloric unit (1 kg of water heated up 1°C) depended on whether the water was weighed against a brass kilogram in air or in vacuum without the buoyancy of air!

And it had become clear that water does not take quite the same energy to heat it up from 10° to 11° as from 17° to 18°. The specific heat capacity of water around 20°C (a comfortable room temperature) is slightly smaller than at lower temperatures. So, for statements accurate to 0.1% or better, we must state the temperature-region used for the thermal unit.

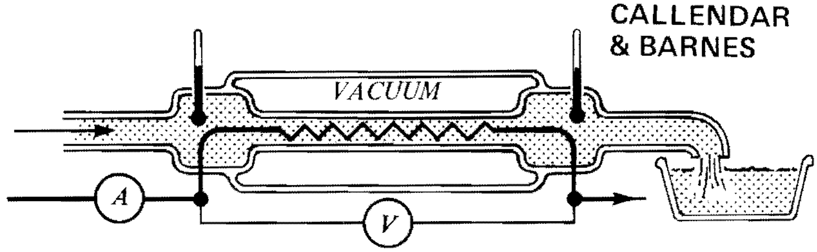
There have been several careful determinations of J in the last hundred years. A few are given below, with vacuum weighing, for a 20°C thermal unit (1 kg of water warmed up from 19.5 to 20.5°C).

DATE	EXPERIMENTER	METHOD	RESULT
1878	JOULE (England):	Water churned. Result of experiment above reduced to weighings in vacuum and corrected to gas-thermometer.	4.172
1879	ROWLAND (Johns Hopkins, U.S.A.):	Water churned by paddle wheel driven by steam engine. Tremendous care over apparatus design and thermometer corrections.	4.179
1892	MICELESCU (France):	Water churning.	4.166
1899	CALLENDAR & BARNES (England):	Continuous flow of water heated electrically. Temperature rise measured electrically.	4.183
1927	LABY & HERCUS (Australia):	Water churned by paddle.	4.1802 ± .0001
1939	OSBORNE et al. (National Bureau of Standards, U.S.A.):	Electrical heating of water.	4.1819



(MANY EXPERIMENTERS)

CALLENDAR & BARNES



continuous flow of water heated by electric current