Further Light on the Source of the Lead in Human Remains from the 1845 Franklin Expedition

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The Royal Navy's 1845 Arctic expedition, commanded by Sir John Franklin, was a disaster from which none of the 129 men who sailed into the Canadian archipelago would return. Hypotheses concerning the source of the high lead levels detected in human remains from the Franklin expedition are re-examined in the light of evidence from cases of occupational exposure and of malicious poisoning. It is argued that there was a significant source of environmental lead exposure during the expedition which was unconnected with any part of the expedition's provisions such as the soldered food cans. Support is given for the proposal that the ships' apparatus for melting snow to produce fresh water, which was of a design hurriedly improvised a decade earlier, produced lead contaminated water when it was operated to a regime which the ship's cooks had previously practised on HMS *Erebus* during the 1839–44 Antarctic expedition under James Clark Ross.

Historical Background

In July 1845, two well-equipped ships of a British naval expedition, 'for the discovery of the Northwest passage and the advancement of science',[1] led by veteran explorer Sir John Franklin, sailed into the Canadian Arctic archipelago and disappeared. None of the 129 officers and men of HM ships *Erebus* and *Terror* survived to tell their story and it would take more than a decade, and vast expenditure of government and private money before the sparse outline of the story of the loss of the Franklin expedition would become known.

The expedition spent the first winter encamped at Beechey Island where three crewmen who died of natural causes were buried. The only significant document recovered, the so-called 'Victory Point record', noted that, after continuing their voyage from Beechey Island, the ships had become trapped in heavy ice in September 1846 and were abandoned in April 1848. The 105 men who remained alive at that time intended to cross King William Island to seek refuge on the North American mainland.

The death toll did not fall evenly on all ranks, the record stating that 'the total loss by deaths in the expedition has been to this date 9 officers and 15 men.' There had been a total of thirty officers (commissioned and warrant) on the two ships, so the nine dead represented 30% or nearly one in three. Discounting the three buried at Beechey Island, the death toll among the

[1] London, The National Archives: Admiralty, Navy, Royal Marines, and Coastguard, (hereafter TNA), ADM 7/187, 'Arctic Expeditions 1845–1848', John Barrow Jnr., foreword to John Barrow Snr's December 1844 letter to Lord Haddington, February 1851.

remaining men equates to 12.5% or one in eight. The reason for this disparity in death rates has puzzled researchers since the record was discovered.

In 1852 the finger of suspicion was pointed at provisions contractor Stefan Goldner, who had supplied the expedition's canned food. His reputation was ruined by a scandal involving putrid meat in Royal Navy stores.[2] Despite being cleared of any blame with regard to 1845 expedition by a Parliamentary Committee,[3] 'there continue to be ill-informed historians who make him the villain of the Franklin tragedy'.[4]

Scientific Background

A new avenue of enquiry was opened up by Beattie's discovery,[5] in 1981 on King William Island, of skeletal remains from an expedition member which were later found to contain high levels of lead. A number of potential sources for the lead were proposed, just one being the soldered seams of the expedition's tin cans. Questions posed by this research led to the exhumation, between 1984 and 1986, of the bodies of the three men, Torrington, Hartnell, and Braine, from the permafrost of Beechey Island. The causes of death could not be determined with any certainty, pneumonia[6] and tuberculosis being suggested, with no physical sign of lead poisoning.[7] High levels of lead were found in the hair of all three men, the source was then asserted to be the soldered seams of the food cans.[8] Further analysis of the hair revealed lead levels of up to 707 μg/g with the caveat that the analysis could not determine whether source was endogenous or exogenous.[9]

The theory that the lead came from the cans was contested on grounds that the canned foods of the day were quite low in lead[10] and that the levels did not correlate with the order in which the men had died.[11] Isotope evidence that the lead in both the solder and human remains did not correspond to a UK geological source, implying an exotic origin, was cited as evidence

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[2] Ardeleanu, C., 'A British Meat Cannery in Moldavia (1844–52)', *The Slavonic and East European Review*, 90(4), 2012, pp. 671-704.

[3] *Report from the Select Committee on Preserved Meats (Navy), Together with the Minutes of Evidence, Appendix and Index*, London, House of Commons, 1852.

[4] Lloyd, C., and J. L. S. Coulter. *Medicine and the Navy 1200-1900*, Vol. IV: 1815-1900, Edinburgh, Livingstone, 1963, p. 101.

[5] Beattie, O. B., 'Elevated bone lead levels in a crewman from the last arctic expedition of Sir John Franklin', In: Sutherland, P., ed, *The Franklin era in Canadian Arctic history 1845–1859*, 131, 1985, pp. 141–8.

[6] Amy, R., Bhatnagar, R., Damkjar, E., Beattie, O. B., 'The last Franklin expedition: report of a postmortem examination of a crew member', *CMAJ*, 135(2), 1986, pp. 115–7.

[7] Notman, D. N., Anderson, L., Beattie, O. B., Amy, R., 'Arctic Paleoradiology: Portable Radiographic Examination of Two Frozen Sailors from the Franklin Expedition (1845–1848)', *American Journal of Roentgenology*, 149(2), 1987, pp. 347–50.

[8] Beattie, O., Geiger J., *Frozen in time: the fate of the Franklin expedition*, London, Bloomsbury, 1987, p.160.

[9] Kowal, W., Krahn, P. M., Beattie, O. B., 'Lead levels in human tissues from the Franklin Forensic Project', *International Journal of Environmental and Analytical Chemistry*, 35(2), 1989, pp. 119–126.

[10] Farrer, K. T. H., 'Whence Came the Lead in Franklin's Crewmen', *Food Science and Technology Today*, 3(2), 1989, pp. 93–4.

that the lead came from the cans.[12] Farrer[13] contested that conclusion on the basis of isotopic matches from British archaeological contexts and questioned the validity of the geological data used. He also proposed a number of additional possible sources of lead, citing cases of ship-board lead poisoning in which drinking water had absorbed lead from water pipes and lead-lined cisterns. More recent geological data[14] supports a British origin for the lead.

A later proposal for a water-borne source of lead[15] is developed further in the current paper. Farrer also noted the problems of hair analysis, including that lead from external sources may bind with sulfhydryl groups on the hair protein and suggested that the lead in Torrington's hair may have been exogenous contamination. He also suggested that the normal background levels of lead in the mid-nineteenth century population would have been 'very high' but could not be quantified in the absence of relevant control studies.

Keenleyside et al. used X-ray fluorescence in the analysis of a large accumulation of bones from site NgLj-2, discovered in 1993 on the Western coast of King William Island.[16] Of eight vertebrae, the levels varied from 284.65 g/g to 1739.85 g/g, a much wider range than could be expected if the source of the lead had been the men's rations. Individual disarticulated bones were assigned to seven distinct skeletons, numbered in order of increasing lead levels. Unassigned bones were judged to represent a further four individuals. It was noted that the distribution of lead between bones was quite different from that observed in skeletons having acquired lead from environmental exposure only. The calcaneus/tibia ratio of lead levels was significantly higher than that found in a study of lead smelter workers averaging 9.2 years exposure,[17] which implied a comparatively short duration exposure. The Calcaneus is mainly trabecular bone, hence a relatively short term reservoir of skeletal lead compared with the (mainly cortical) shaft of the tibia.

Based on a linear relationship between tibial lead levels and Cumulative Blood Lead Index (CBLI), with the assumption that half the lead had been accumulated prior to the 3-year duration of the expedition, blood lead levels were estimated to be between 200 and 500 µg/dl (i.e. up to ten times the recommended safe limit) with the implication that the men must have suffered

[11] Trafton, S. J., 'Did Lead Poisoning Contribute to Deaths of Franklin Expedition Members? ', *Information North*, 15, 1989, pp. 1–4.

[12] Kowal, W., Beattie, O. B., Baadsgaard, H., Krahn, P. M., 'Source Identification of Lead Found in Tissues Of Sailors from the Franklin Expedition of 1845', *Journal of Archaeological Science*, 18, 1991, pp. 193–203.

[13] Farrer, K. T. H., 'Lead and the Last Franklin Expedition', *Journal of Archaeological Science* , 20, 1993, pp. 399–409.

[14] Rohl, B. M., 'Lead Isotope Data from the Isotrace Laboratory, Oxford: Archaeometry Data Base 2, galena from Britain and Ireland', *Archaeometry*, 38(1), 1996, pp. 165–180.

[15] Battersby, W., 'Identification of the Probable Source of the Lead Poisoning Observed in Members of the Franklin Expedition', *Journal of the Hakluyt Society*, 2008.

[16] Keenleyside, A., Song, X., Chettle, D. R., Webber, C. E., 'The Lead Content of Human Bones from the 1845 Franklin Expedition', *Journal of Archaeological Science*, 23, 1996, pp. 461–5.

[17] Cake, K.M., Bowins, R. J., Vaillancourt, C., Gordon, C. L., McNutt, R. H., Laporte, R., Webber, C. E., Chettle, D. R., 'Partition of Circulating Lead Between Serum and Red Cells is Different for Internal and External Sources of Lead', *American Journal of Industrial Medicine*, 1996, 29(5), pp. 440–45.

from severe lead poisoning. However, the proposal that this group experienced such a strong degree of poisoning seems to conflict with the physical achievement of dragging heavily laden sledges from the location where the ships were deserted to where their bones were found – a distance of approximately 100 kilometres.

It should be noted that the blood lead estimate was based on tibiae from only the first four of the seven assembled skeletons as these bones were not present in skeletons 5 to 7. While the highest lead level in the extant tibiae is 151.4 µg/g, that for skeleton 7 can be approximated, by scaling from the level in the radius, to be about 320 µg/g. Using this value, the upper bound of estimated blood lead level would be implausibly high at over 1000 µg/dl. However, the established linear relationship between tibial lead and CBLI has been questioned,[18] and curvilinear models proposed.[19] The implication in this case is that blood lead would be overestimated by applying a linear relationship derived from studies of moderately exposed workers.

Millar et al.[20] presented a statistical analysis of a subset of the NgLj-2 data to elucidate the pattern and consequences of the variation of lead exposure among the expedition participants as a whole. The assumption that the men accumulated half their lead burden prior the expedition was questioned on the basis that it would imply an improbably low background blood lead level for the era, and it was alternatively proposed that they accumulated lead at largely the same rate both before and during the expedition, thus avoiding the need to infer the existence of a potent source of lead contamination on the ships. The blood lead range was thus recalculated as 38–94 µg/dl, suggesting that there would have been a wide range in the intensity of symptoms with those with highest burdens likely suffering some debility.

However, it should be noted that this steady-state model of lead accumulation conflicts with the conclusions of Keenleyside et al.[21] regarding the general lead distribution within the skeletons and of the calcaneus/tibia ratios. Additionally, the very high correlation visible in the calcaleus/tibia graph, in comparison with those for studies of smelter workers, e.g. Fleming et al.,[22] may suggest a shared chronology of lead exposure which would be unlikely in the case that most of the lead had been acquired prior to the expedition. It was noted that the high lead levels detected in Torrington's hair may be exogenous contamination resulting from his duties as a stoker and it was also suggested that the extreme lead levels found in distal segments Torrington's hair would indicate that he was exposed to high levels of lead at the time of departure.

[18] Healey, N., Chettle, D. R., McNeill, F. E., Fleming, D. E. B., 'Uncertainties in the Relationship between Tibia Lead and Cumulative Blood Lead Index', *Environmental Health Perspectives*, 116(3), 2008, p. A109.

[19] Behinaein, S., Chettle, D. R., Egden, L. M., McNeill, F. E., Norman, G., Richard, N., Stever, S., 'Nonlinearity in the relationship between bone lead concentrations and CBLI for lead smelter employees', *Journal of Environmental Monitoring*, 14(12), 2012, pp. 3267–75.

[20] Millar, K., Bowman, A. W., Battersby, W., 'A Re-Analysis Of The Supposed Role of Lead Poisoning in Sir John Franklin's Last Expedition, 1845–1848', *Polar Record*, 51(3), 2014, pp. 224–38.

[21] Keenleyside, A., Song, X., Chettle, D. R., Webber, C. E., 'The Lead Content of Human Bones from the 1845 Franklin Expedition', *Journal of Archaeological Science*, 23, 1996, pp. 461–5.

[22] Fleming, D. E., Boulay, D., Richard, N. S., 'Accumulated Body Burden and Endogenous Release of Lead in Employees of a Lead Smelter', *Environmental Health Perspectives*, 105(2), 1997, pp. 224–33.

Martin et al.[23] used synchrotron X-ray fluorescence (SR-XRF) and laser ablation/mass spectroscopy to analyse small samples of bone from Beattie's campaigns on Beechey and King William Islands with the conclusion that although the bones contained high levels of lead, the analysis did not implicate the tins as the source, and that both the µXRF maps and the distribution of the isotope ratios implied that the lead was absorbed over a long period with no evidence of a massive increase in lead exposure during the duration of the expedition.

However, lead isotope ratio evidence cannot itself elucidate the chronology of exposure without evidence that the isotopic signature of the lead the men were exposed to during the expedition was distinguishable from that which they had been exposed to throughout their earlier lives. Equally, the lack of a detailed methodology to elucidate the chronology of the lead uptake from such µXRF maps precludes reliable estimates of the relative proportion of lead which these individuals absorbed before or during the expedition.

The authors note that 'the high levels of Pb in the hair samples reported by Kowal et al. would be better indicators of environmental exposure to Pb rather than ingestion, and may be indicative of Pb from sources other than the solder.' This suggestion that the hair data might be a clue to the source of the lead deserves further investigation.

Hair

Hair from each of the Beechey Island bodies was analysed in 10mm segments and the results published for the root plus the range and mean but not for individual segments.[24] Hair is composed of keratin, which has a high surface density of sulfhydryl groups which have a strong affinity for heavy metals. Environmental lead chemically binds to hair like a permanent invisible dye. It is not removed by washing with detergent[25] which makes it difficult to determine whether lead detected in the hair is derived from within the body or external contamination.

Comparison of the Beechey island hair data with two cases of malicious lead poisoning and a case of occupational exposure is instructive:

- A 41 year old male schoolteacher was fatally poisoned with lead oxide(II) by his wife over a period of 1.5 years. Blood lead was 158 µg/dl about 5 months before death. The average lead concentration in scalp hair of 3-5 cm length was 30.2 µg/g and in pubic hair 33.7 µg/g.[26]

[23] Martin, R. R., Naftel, S., Macfie, S., Jones, K., Nelson, A., 'Pb Distribution in Bones from the Franklin Expedition: Synchrotron X–Ray Fluorescence and Laser Ablation/Mass Spectroscopy', *Applied Physics A*, 111(1), 2013, pp. 23–9.

[24] Kowal, W., Krahn, P. M., Beattie, O. B., 'Lead levels in human tissues from the Franklin Forensic Project', *International Journal of Environmental and Analytical Chemistry*, 35(2), 1989, pp. 119–126.

[25] Clarke, A. N., Wilson, D. J., 'Preparation of Hair for Lead Analysis', *Archives of Environmental Health*, 28(5), 1974, pp. 292–6.

[26] Lech, T., 'Exhumation Examination to Confirm Suspicion of Fatal Lead Poisoning', *Forensic science international,* 158, 2006, pp. 219–23.

- A 43 year old woman was poisoned with lead nitrate in her coffee, estimated at 100 mg Pb per cup, by her schoolteacher husband over a period of 10 months. Her symptoms required her to give up work and she was hospitalised for 1 month. The peak average lead concentration in a bundle of five 1cm hair segments was 6.5 picomol Pb per 47.2 µg segment, i.e. approximately 29 µg/g.[27] For comparison, the mean Pb values for 1cm segments of scalp hair of Leading Stoker Torrington were up to 707 µg/g with 330 µg/g at the root and a mean of 565 µg/g.[28] These values are up to 21 times greater than in the above malicious cases of lead poisoning.

- Sixteen employees of a battery factory had mean distal hair lead levels varying from 124 to 1381 µg/g with an arithmetic mean of 476 µg/g.[29]

The hair lead levels from Beechey Island are very much higher than the two cases of ingested lead exposure yet within the range of levels reported for the battery factory. This would suggest that the lead in the men's hair may be external contamination received during the course of the expedition.

In cases of environmental exposure, lead levels generally show an increasing trend from proximal to distal. Only Torrington has the minimum lead level, at the root end where it would be expected in a case of external contamination. However, this deviation from the expected pattern should not rule out the diagnosis of external contamination as for two of the eight family members in the battery factory study the minimum lead level was also at an intermediate location instead of the root end. The lead levels in the Beechey Island hair vary significantly between individuals: the mean value for Torrington is 73% higher than Hartnell's whose mean value is in turn 45% higher than Braine's.[30] Interestingly, the trend parallels their precedence as petty officer, able seaman, and Royal Marine.

The published values for bone lead do not allow a similar comparison. While Torrington had the highest hair lead, his bone lead was 110-151 µg/g dry weight[31], i.e. within the overall range of 69-183 µg/g dry weight which Kowal et al.[32] reported for all three. While Amy et al.[33] reported that they analysed bone samples from rib, clavicle and radius from Torrington, Kowal et

[27] Grandjean, P., 'Lead Poisoning: Hair Analysis Shows the Calendar of Events', *Human & Experimental Toxicology*, 3, 1984, pp. 223–8.

[28] Kowal, W., Krahn, P. M., Beattie, O. B., 'Lead levels in human tissues from the Franklin Forensic Project', *International Journal of Environmental and Analytical Chemistry*, 35(2), 1989, pp. 119–126.

[29] Fergusson, J. E., Hibbard, K. A., Ting, R. L. H., 'Lead in Human Hair: General Survey - Battery Factory Employees and their Families', *Environmental Pollution Series B, Chemical and Physical* , 2(3), 1981, pp. 235–48.

[30] Kowal, W., Krahn, P. M., Beattie, O. B., 'Lead levels in human tissues from the Franklin Forensic Project', *International Journal of Environmental and Analytical Chemistry*, 35(2), 1989, pp. 119–126.

[31] Amy, R., Bhatnagar, R., Damkjar, E., Beattie, O. B., 'The last Franklin expedition: report of a postmortem examination of a crew member', *CMAJ*, 135(2), 1986, pp. 115–7.

[32] Kowal, W., Krahn, P. M., Beattie, O. B., 'Lead levels in human tissues from the Franklin Forensic Project', *International Journal of Environmental and Analytical Chemistry*, 35(2), 1989, pp. 119–126.

[33] Amy, R., Bhatnagar, R., Damkjar, E., Beattie, O. B., 'The last Franklin expedition: report of a postmortem examination of a crew member', *CMAJ*, 135(2), 1986, pp. 115–7.

al.[34] mention two samples of rib plus one each from radius, skull, and vertebra but do not disclose which of the three men they relate to or the lead values for each sample. From the scant information available it is impossible to say whether the skeletal lead levels of the three men display a pattern similar to the hair lead or not. However, most of the hair sampled must have grown since the departure of the expedition and so can only reflect conditions during the voyage. While there is evidence of small scale tinsmithing during the expedition to convert salvaged food cans into useful articles such as pannikins and canteens, the lead exposure which would be expected from such activity is far below that of the industrial environments which provide the closest parallels to the levels observed.

In the absence of evidence for any activities during the winter of 1845–6 which might have resulted in severe airborne lead pollution the possibility that the lead in the hair is due to washing in lead contaminated water must be considered.

Water

If the drinking water on board the ships was contaminated with lead then it is the likely source of lead found in the bones and soft tissues and also, through bathing, the cause of the high levels found in the hair. Cleanliness was of great importance to the Victorian Navy as prior to the development of the germ theory of disease, cleanliness was regarded as the principal requisite for the preservation of health. When *Hecla* and *Fury* spent the winter of 1824–5 at Port Bowen in Prince Regent's Inlet during Parry's third voyage the ships' empty cable tiers were used to provide facilities for the men to wash themselves from head to foot in tubs of hot water.[35]. Francis Crozier, a midshipman on *Hecla*, may have ensured the practice was continued when he captained *Terror* during the 1845 expedition. A typical shipboard routine would have clothes washed on Mondays and Thursdays while the men washed and shaved on Saturday afternoon in preparation for Divisions on Sunday.[36]

Battersby[37] proposed that the 'unique water system fitted to the expedition's ships'was the cause of the observed lead exposure. A revised interpretation of several points of evidence was presented in a later paper.[38] The 1837 profile plan of *Terror* largely represents the ship as it was in 1836 with amendments relating to the installation of the screw propeller in 1845 but it does not fully reflect the state of ship at the time of the final voyage. The plan shows the Perkins high pressure hot water heating system which had been installed on the instructions of Edward Belcher, but this had subsequently been dismantled after repeatedly failing during Back's 1836 expedition. Reports in *The Times* and *Illustrated London News* on the departure of the 1845

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[34] Kowal, W., Krahn, P. M., Beattie, O. B., 'Lead levels in human tissues from the Franklin Forensic Project', *International Journal of Environmental and Analytical Chemistry*, 35(2), 1989, pp. 119–126.

[35] Parry, W. E., *Journal of a Third Voyage for the Discovery of a Northwest Passage, from the Atlantic to the Pacific; Performed in the Years 1824-25*, London, Murray, 1826, pp. 49.

[36] Fordyce, A. D., *Outlines of naval routine*, London, Smith, Elder, & Co., 1837, pp. 91–3.

[37] Battersby, W., 'Identification of the Probable Source of the Lead Poisoning Observed in Members of the Franklin Expedition', *Journal of the Hakluyt Society*, 2008.

[38] Battersby, W., Carney, P., 'Equipping HM Ships Erebus and Terror, 1845', *International Journal for the History of Engineering & Technology*, 81(2), 2011, pp. 192–211.

expedition erroneously claim the ships were heated by a system of hot water pipes when in fact the tried and trusted Sylvester warm-air stove had been installed on both *Erebus* and *Terror* prior to their departure for the Antarctic in 1839. The tank over the galley stove, installed in 1836 and still in place in 1845, was intended to produce fresh water by melting snow, not by distillation.

In contrast to Battersby's proposal that a unique design of water making equipment was fitted to *Erebus* and *Terror* immediately prior to their final expedition in 1845, it appears the water making apparatus was unique to the two ships but was essentially unchanged from the two expeditions prior to the fatal 1845 expedition, i.e. George Back's 1836 expedition in HMS *Terror*, and James Ross' Antarctic expedition of 1839–43 in *Erebus* and *Terror*. This paper proposes that the water produced was sometimes pure, and at other times contaminated with lead, depending on how the equipment was operated.

Fraser's Patent Galley Stove

Erebus and *Terror* were initially modified for service in polar seas in 1836 in preparation for a mission to relieve a fleet of whale ships beset in ice off the coast of Greenland. The work was supervised by Chatham dockyard foreman William MacPherson Rice on the instructions of Commander Edward Belcher. In the event neither ship was used, James Ross instead taking command of a hired whaler, the *Cove*. HMS *Terror* was then assigned to Captain George Back's attempt at geographical discovery on the Arctic shores. Back raised his pennant on HMS *Terror* on 13 May 1836, and on the 16th he wrote to the Admiralty[39] to request the substitution of the galley stove, which he stated was suitable for a crew of 260 men, for one more appropriate to the *Terror*'s complement of 60. The stove was changed without delay but all was not entirely satisfactory as Back wrote again[40] on the 20th with information from his first lieutenant that 'there is no scuttle over the condenser for the purpose of throwing in snow to melt'. The mention of a condenser, and the reference to melting snow, hints at the dual purpose of the apparatus in question: to melt snow to satisfy the ship's daily requirement for fresh water, and to condense the excess steam emanating from the galley stove.

Steam escaping from the galley stove on Sir Edward Parry's first 'voyage of discovery' had caused untold misery by condensing on the beams and bulkheads of the ship. For his second voyage, manufacturers Lamb and Nicholson provided modified stoves, which both condensed the steam and used waste heat from the smoke to melt snow to produce 'sixty-five gallons of pure water from morning till night; a quantity, of course, more than sufficient for our whole consumption'.[41] Despite the efficiency of this apparatus for fulfilling the daily water requirements, there was an occasional need to melt ice in much greater quantities. In June 1822, with the impending breakup of the ice threatening to release his ships from their winter quarters and their water tanks nearly empty, 'each ship commenced melting snow in her coppers for filling

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[39] TNA, ADM 1/1584, B102, Letter of George Back to Charles Wood, 16 May 1836.

[40] TNA, ADM 1/1584, B111, Letter of George Back to Charles Wood, 20 May 1836.

[41] Parry, W. E., *Journal of a Second Voyage for the Discovery of a North-west Passage from the Atlantic to the Pacific: Performed in the Years 1821–22–23*, London, Murray, 1824, pp. vi–vii.

the tanks'.[42] Both James Ross and Francis Crozier served as midshipmen on HMS *Fury* during that voyage so undoubtedly they will have been familiar with that operation.

The Fraser stove and its attachments having performed satisfactorily on *Terror* during the 1836 expedition it would be natural that *Erebus* would be modified to the same standard so that both ships would be identically equipped for the 1839 Antarctic expedition. Although steam engines and screw propellers were installed on both ships in 1845, there is no reason to suppose that any significant changes were made to the galley arrangements. A visitor to the ships commented 'we were amused with the cooking-apparatus. The contrivance for turning the snow into a constant supply of water is almost worthy of the inventor of the steam-engine'.[43]

Drawings

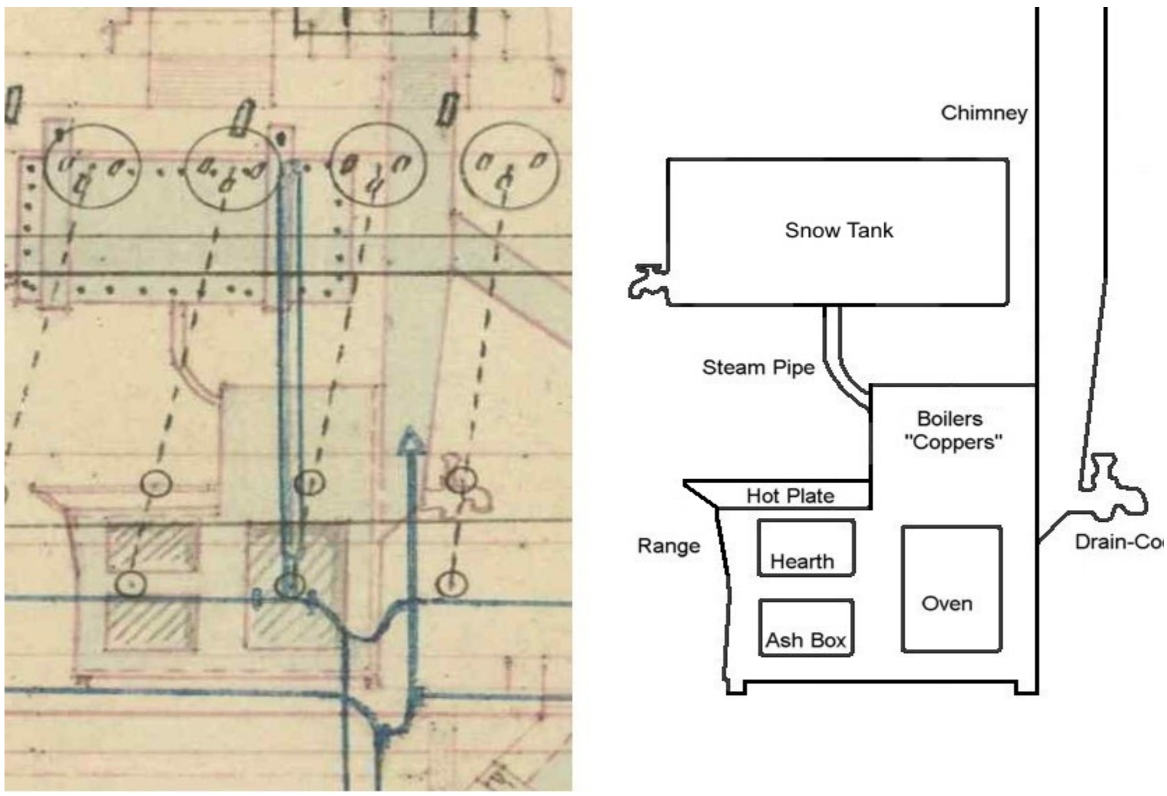


Figure 1 (above) is a detail from the 1837 profile of HMS *Terror*, with an explanatory key, showing the Fraser galley stove and the snow-tank which Back refers to as the 'condenser'. From its dimensions, the tank appears to be a standard iron water tank of the 'quarter square' variety, having a capacity of 98¾ imperial gallons (449 litres).[44] The stove and the tank appear to be connected by a gently curving pipe approximately 2" in diameter. Although the pipe is not shown on the corresponding drawing of HMS *Erebus* as fitted for the 1839 expedition we can be

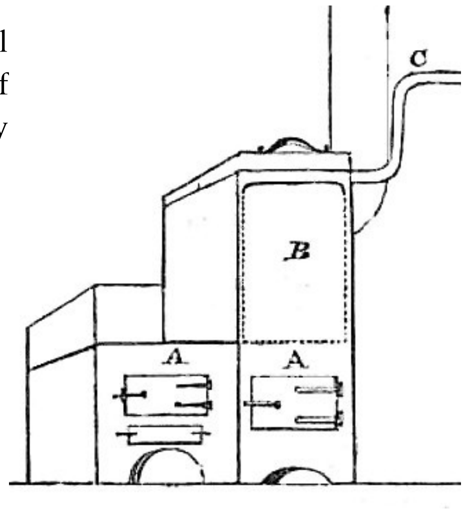
[42] ibid, p. 240.

[43] The Arctic Expedition, *Literary Gazette*, London, 10 May 1845, p. 296.

[44] Contents, Weight, and Size of the Iron Water Tanks supplied to His Majesty's Ships, *United Service Journal*, London, Colburn & Bentley, 2, 1832, p. 534.

confident that it existed as without it the tank could have fulfilled neither of its two functions of melting snow for water and preventing the galley being filled with steam.

The stove shown in Figure 2 (right) bears a close visual similarity with that of Figure 1 and is identified as 'one of Frazer's patent sort' by an inventor who had independently recognised the design's suitability for distilling seawater.[45]



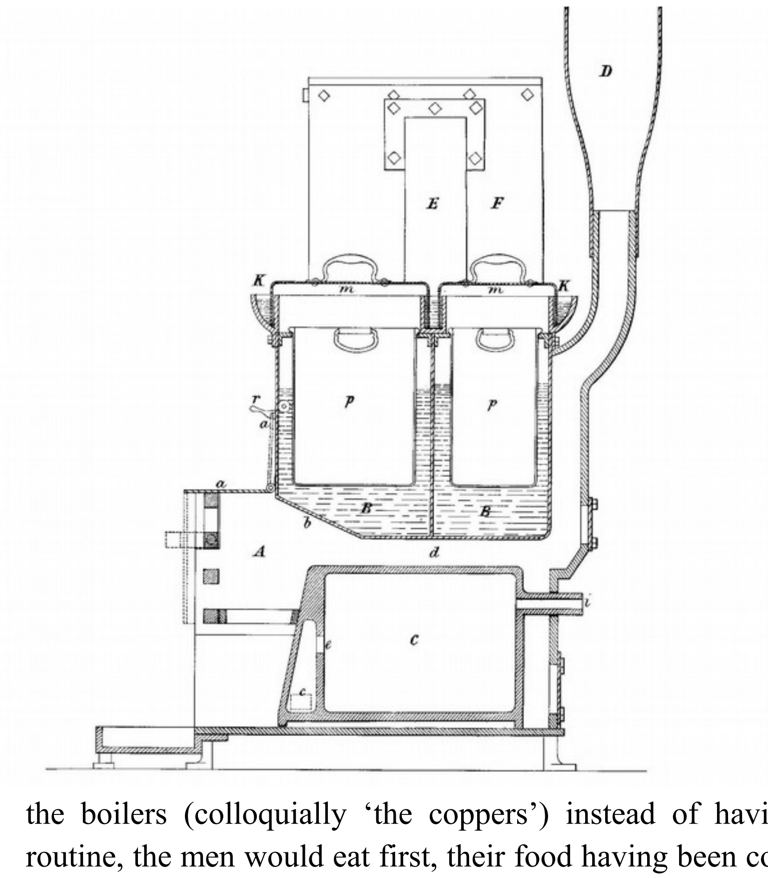


Figure 3 (left) is a section of the stove from John Moxon and James Fraser's patent for a stove able to distil seawater at the same time as cooking.[46] The stove shown has an unusual tandem arrangement of boilers which allows a connection for each boiler to be replenished with seawater warmed in the water jacket of the large floor-standing condenser. Although the plans suggest that the stoves fitted to *Erebus* and *Terror* had two boilers side-by-side, this patent provides useful insight into their internal structure and functioning.

In contrast to the larger stoves used by the Royal Navy, a single hearth heats the range, hot plates, and the boilers (colloquially 'the coppers') instead of having separate fires. According to naval routine, the men would eat first, their food having been cooked in the boilers. The officers' meals would then be prepared on the range side of the stove, which allowed a more refined sort of

[45] Baker, E. W. Jnr., 'Apparatus for Freshening Salt Water', *The Mechanics' Magazine*, 18, 16 March 1833, p. 386.

[46] GB Patent 4706, Moxon, J., Fraser, J., *Certain Improvements in Ships' Cabooses or Hearths etc*., UK Intellectual Property Office, 1822.

cuisine. Traditionally, the men's meat was packed in nets, and the puddings in bags, then immersed in the boiling water.[47] The stove shown in the patent drawing has the innovation of using internal cooking kettles (referred to as 'internal cases or steamers' in the patent specification) in a bain-marie type water bath although there is no independent confirmation that they were present in 1845.

The boilers are depicted with steam-tight lids and a port at the side for the egress of steam – a result of James Fraser's ambitions of selling his stoves for distillation of sea water. Many other manufacturers of the era had similar ideas, invariably downplaying the energy cost involved. Distillation had been trialled in the Arctic on HMS *Racehorse* in 1773 using 'Dr. Irving's apparatus for making salt water fresh'.[48] Subsequent expeditions melted snow and ice to make fresh water as the energy required is only about one eighth of that needed for distillation.

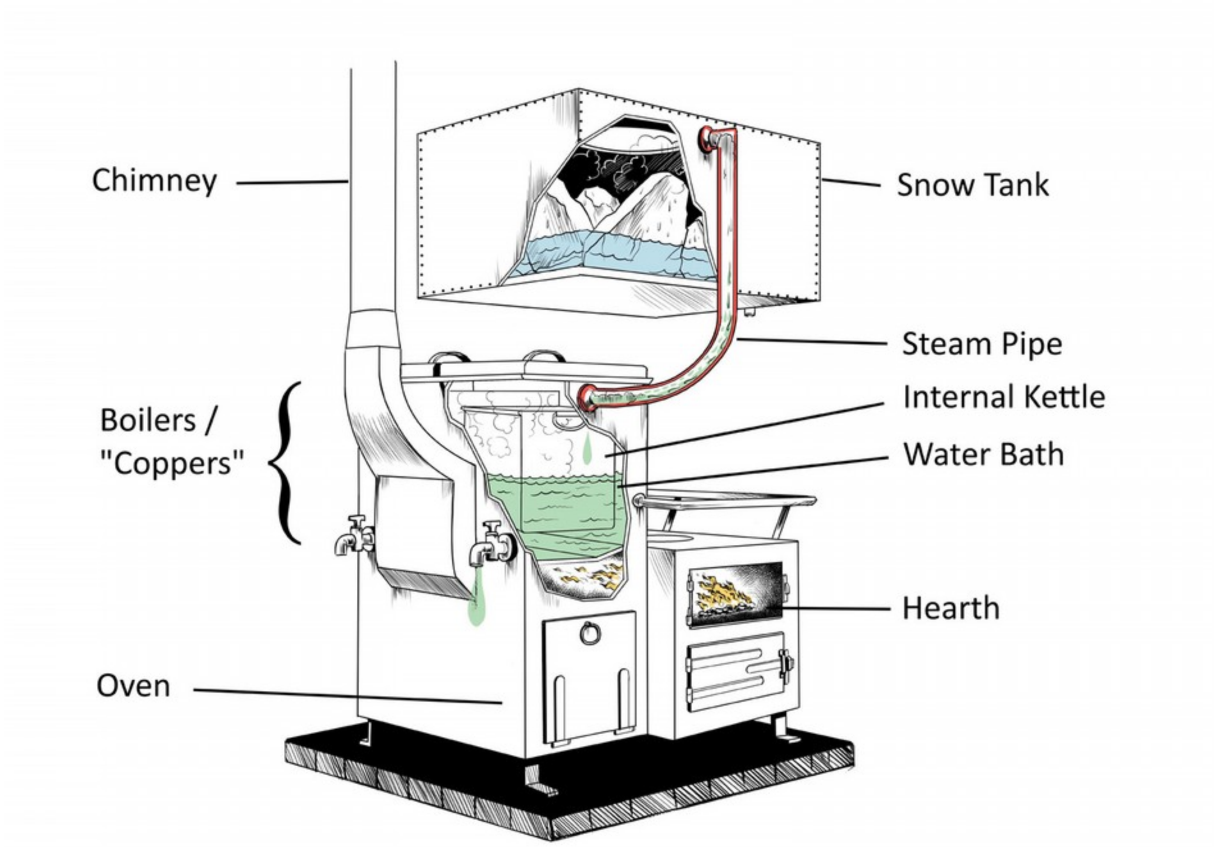


Figure 4 (above) is an artist's reconstruction of the stove and water-maker based on the available evidence. The fire heats the hot-plates while the burning gasses pass under the boilers, and over the oven, before escaping via the chimney. In the boilers/coppers, the food in the internal kettles is heated from below by the water bath and by steam from above. Drain-cocks allow discharge of the boiler water to facilitate the daily routine of cleaning and inspection. Excess steam passes up the pipe to the snow tank, where it condenses, giving up its heat energy to

[47] Macdonald J., *Feeding Nelson's Navy – The true story of food at sea in the Georgian era*, London, Chatham Publishing, 2004, p. 101.

[48] Equiano, O., *The Interesting Narrative of the Life of Olaudah Equiano, or Gustavus Vassa, the African, Written by Himself*, London, via Project Gutenberg, 1789.

the snow and ice packed inside. The water produced can be regarded as completely wholesome, being mostly meltwater with about ten percent condensed steam.

As the range, hot plates, oven, and boilers, are heated by a single fire, considerable planning and co-ordination is required to make use of all parts simultaneously to ensure the most economical use of fuel. Although the Fraser stove received considerable praise, the snow tank did have a number of weaknesses which became apparent during the 1839 Antarctic expedition.

Weaknesses

In March 1847, when the first expedition to search for Franklin was being planned, James Ross proposed that the ships required should be 'fortified and equipped in every respect as were the *Erebus* and *Terror* for the Antarctic Seas'. The plans of *Enterprise* and *Investigator* do indeed show that a very similar arrangement of galley stove and overhead tank were fitted but there are subtle differences to the earlier arrangement. The new tank was longer and pierced by two vertical tubes: one to allow the stove's chimney to pass through thus directly heating the tank, and one closable by a removable glass lid to allow illumination or ventilation as required.[49] Apart from *Enterprise* and *Investigator*, none of the plans of the Royal Navy's ships involved in the search for Franklin show an arrangement of tank and stove comparable to that of *Erebus* and *Terror*, instead only the silhouette of the traditional type of stove as used on Parry's *Hecla* and *Fury* can be seen.

William Rice, by now Master Shipwright of Woolwich Dockyard, states that *Enterprise* and *Investigator* were fitted with 'Bowser's Fire hearth with Snow tank for supply of fresh water to which also has been adapted a mode of ventilation'.[50] The stoves shown in the plans of these ships are similar in form to those in the plans of *Erebus* and *Terror*. These modifications presumably derived from experience on the Antarctic expedition which Ross will have passed on to Rice. The need for improved ventilation is attested, for example, in Sergeant Cunningham's journal entry for 25 March 1841 which reports: 'Got the ice tank down from over the Cooks Coppers [i.e. the Fraser Stove] and a funnel Shipped on the scuttle which will carry the Steam off the Lower deck and thereby make it much comftabler [sic] and wholesome for everyone'.[51]

The change to route the chimney through the tank will have greatly improved the ice melting performance. In contrast to the Lamb and Nicholson design used by Parry in which the melting tank was heated by the hot flue gasses as they escaped up the chimney, the system improvised at Chatham for *Terror* in 1836 heated its snow tank indirectly via the intermediary of steam. This would necessarily entail considerable loss of heat to the environment from the walls of the steam pipe before any steam reached the tank, and seriously compromise the ice-melting capacity. If the ship's daily water requirement was to be satisfied by the melting tank alone, then

[49] Admiralty plans of HMS *Investigator,* in Cohen, A., *Lost Beneath the Ice: The Story of HMS Investigator*, Toronto, Dundurn, 2013, pp. 44–52.

[50] Armstrong, A., *A Personal Narrative of the Discovery of the North-west Passage*, London, Hurst & Blackett, 1857, p. 608.

[51] Campbell, R., 'The Journal of Sergeant William K. Cunningham, R.M. of HMS Terror', *Journal of the Hakluyt Society*, 2, 2009, p. 82.

it is likely that the stove would need to be fired for longer than would be the case if it was purely used for cooking. This weakness may not have been an issue during Back's 1836 expedition in *Terror*, as due to the failure of the Perkins heating system, the galley stove may have been used around the clock for warming the mess deck.

An additional potential problem with the 1836 design of snow tank is that while the steam pipe was losing heat to the air in the galley, some of the steam was necessarily condensing on the inside walls of the pipe. There seems to be no reasonable alternative material for the steam pipe other than lead. Lead water pipes were ubiquitous including, on warships, the 'two lead pipes that have brass screws at the ends' associated with the Truscott's force pump[52], and were manufactured in the Navy's own lead mill at Chatham dockyard where *Terror* was fitted out in 1836. Lead was considerably cheaper than brass or copper, and the process to manufacture seamless tubes from those metals would not be invented until 1838. The condensate, running down the inside of the pipe as a stream of freshly distilled water acidified by atmospheric carbon dioxide, would have dissolved lead from the walls of the pipe and carried it back down to mix with the water in the boilers/coppers.

If the internal kettles shown in the patent drawing were used, then the food within would never come into contact with the contaminated boiler water. If the kettles were omitted then the provisions would have necessarily been immersed in lead contaminated water. In this case the food may have picked up some lead but as the salt meat and dry provisions will have been previously steeped in fresh water for many hours they could be expected to lose water during cooking rather than absorbing much of the tainted water they were surrounded with. Any such lead contamination of food could be expected to be distributed equally between the men, in contrast to the highly non-uniform distribution attested to by the remains from the 1845 expedition.

Back's Arctic Expedition 1836

Nothing in the historical record suggests that George Back's 1836 expedition in HMS *Terror* suffered from lead poisoning, although the expedition was a near disaster in which the Perkins heating system failed, many of the ship's company developed scurvy[53], and the ship barely managed to reach home waters in a semi-wrecked state One of the few things which Back could praise on that expedition was 'Fraser's fire hearth and coppers'.[54]

Did Back's men suffer from scurvy, or lead poisoning? There can be considerable overlap between early symptoms of vitamin C deficiency and of lead poisoning. However, the *Terror*, with a complement of sixty, was victualed for eighteen months with only 798 lbs of lemon juice which equates to a mere 40% of the standard daily ration of one ounce per man per day. If this was the ration implemented then scurvy would have been inevitable. In connection with the

[52] Burney, W., ed., *A New Universal Dictionary of the Marine*, London, Cadell, Davis, & Murray, 1830, p. 391.

[53] Back, G., 'A Brief Narrative of the Recent Voyage of H.M.S. Terror', *Journal of the Royal Geographical Society*, 7, 1837, pp. 457–60.

[54] Back, G., *Narrative of an expedition in H.M.S. Terror, undertaken with a view to geographical discovery on the Arctic shores, in the years 1836-7*, London, Murray, 1838, p. 5.

scurvy outbreak, it was reported that 'those who used least of either tobacco or ardent spirits came best off'.[55]

Alcohol and smoking are both recognised factors which cause depletion of ascorbate - in the metabolism of alcohol and in combating oxidative stress caused by smoking. The result may be vitamin C deficiency for individuals with an inadequate diet. Low level lead exposure also causes oxidative stress[56] and has been postulated to lower serum ascorbic acid levels.[57] The fact that a correlation was noted between the severity of scurvy and the consumption of alcohol and tobacco may be a pointer that lead exposure comparable to that deduced for the 1845 expedition did not occur during Back's 1836 expedition. Had there been such a pattern of lead exposure, then interactions between vitamin C and blood lead may have masked the reported correlation of the incidence of scurvy with tobacco and alcohol consumption.

The Antarctic 1839–43

In contrast to the Arctic expeditions which overwintered in the ice, the 1839–43 Antarctic expedition in *Erebus* and *Terror* anchored in the more habitable climes of Tasmania, New Zealand, and the Falkland Islands before making forays into the ice-pack in the Austral summers of 1840–41, 1841–2, and 1842–3. There are no reports hinting at lead poisoning during this expedition, instead, in his published narrative, Ross only remarks on the shortness of the sick list.[58]

The *Terror*'s snow tank was tested during the first season in the ice. Sergeant Cunningham's journal for 13 Feb 1841 records 'Large pieces of Ice falling from the Ropes aloft which gathered up and put in the Ice Tank for Thawing'.[59] The ship's log for 16 February 1841 includes the note: 'Rec'd 70 galls in the tanks from the ice'.[60] The output of 70 gallons of water three days after the ice went into the tank compares poorly with the daily 65 gallons Parry reported for his ice melter and, while not conclusive, it is another clue that the combination of Fraser stove and snow tank could not routinely produce the daily water requirement. However, *Erebus* and *Terror* had already produced more than 12 tons of fresh water between them in the previous few weeks by following Parry's example from June 1822 by bulk ice-melting in the 'coppers'.[61,62]

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[55] The Voyage of H.M.S. Terror, Commanded by Captain Beck [sic] (From the *Londonderry Journal*), *St James Chronicle and General Evening Post*, London, 12 September 1837, p. 3.

[56] Ahamed, M., Siddiqui, M. K., 'Low level lead exposure and oxidative stress: current opinions', *Clinica Chimica Acta*, 383(1–2), 2007, pp. 57–64.

[57] Simon, J.A., Hudes, E. S., 'Relationship of Ascorbic Acid to Blood Lead Levels', *Journal of the American Medical Association*, 281(24), 1999, pp. 2289–93.

[58] Ross, J. C., *A Voyage of Discovery and Research in the Southern and Antarctic Regions During the Years 1839-1843*, 2 vols, London, Murray, 1847, 2, p. 379.

[59] Campbell, R., 'The Journal of Sergeant William K. Cunningham, R.M. of HMS Terror', *Journal of the Hakluyt Society*, 2, 2009, p. 78.

[60] TNA, ADM 55/134, 'Terror: Log, 1 Dec 1840 to 31 Dec 1841', p. 80.

[61] TNA, ADM 55/50, 'Erebus: Log, 1 Jan 1841 - 31 Dec 1841', 6-9 Feb 1841, pp. 45–51.

Bulk Watermaking to Fill the Tanks

The simplest way to prepare the Fraser stoves for bulk ice melting would be to lift out the internal cooking kettles (if present), then load the boilers with chunks of freshwater ice. The newly made water would then issue from the open drain cocks as the ice melted. Cunningham described 'Thawing Ice in the Coppers all day and night'[63], but the melting process could not have continued for the whole 24 hours due to stove being needed for cooking the men's meals. When ice melting re-commenced after the men's food had been cooked it would have been logical for the cooks to retain some of the hot water in the boilers to get the ice melting off to a good start. They could not have been aware that, during cooking, condensation in the steam pipe would have contaminated the boiler water with lead dissolved from its walls.

A contemporary memoir of the US Navy suggests it was not unknown for taints from the boiler water to be carried over into drinks when, after dinner, water was heated in the boilers to brew tea 'which, consequently, possesses a flavor not unlike that of shank-soup'.[64] The first water drawn from the drain cocks is likely to have been rich in lead, with the concentration diminishing rapidly as more and more ice was melted.

The daily water ration of around a gallon per man was traditionally served out immediately after the mid-day meal[65] so it is probable that this lead-rich 'first-draw' water was consumed during the few days each ship was melting ice. Alternatively, if the lead-rich water was conveyed to the tanks then the lead concentration would have been greatly diluted by mixing with the purer water produced later during the ice melting process.

The Second Antarctic Season, 1841–2

The pattern was similar during the second season of exploration. Many tons of ice were loaded while *Erebus* was docked to an ice floe for six hours on 23 Dec 1841, an operation noted in the log as 'Emp'd watering'.[66] There then followed a seven day ice-melting marathon, during which the water tanks in use on that voyage (totalling 31 tons) were filled to the brim by the addition of nearly twelve tons of melt-water.

Note that *Erebus*' log books account for water in tons and imperial gallons (of 4.5 litres), with the somewhat unusual ratio of 205 gallons to a ton. The liquid ton was not completely standardised at that time. A liquid ton was generally equated to 210 gallons (equal to the ancient *tun* of 252 wine gallons, each of 3.8 litres), although its replacement by the 224 gallon version was already in progress.

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[62] TNA, ADM 55/134, 'Terror: Log, 1 Dec 1840 to 31 Dec 1841', 7 Feb 1841, p. 71.

[63] Campbell, R., 'The Journal of Sergeant William K. Cunningham, R.M. of HMS Terror', *Journal of the Hakluyt Society*, 2, 2009, p 77.

[64] Melville, H., *White-jacket; Or, The World in the Man-of-war*, London, Bentley, 1850, pp. 92.

[65] Fordyce, A. D., *Outlines of naval routine*, London, Smith, Elder, & co, 1837, pp. 91–3.

[66] TNA, ADM 55/50, 'Erebus: Log, 1 Jan 1841 - 31 Dec 1841', p. 463.

The next day, 31 December 1841, the log indicates that 10 gallons was issued from the tanks followed by a continuous series of 35 days (1 January – 4 February 1842) when the tally remains fixed at 30 tons and 195 gallons.[67] A logical explanation for this apparent hiatus in the daily water issue is that several tons of ice remained after the water tanks had been filled to the brim and that this ice reserve supplied their daily water needs of typically 65 gallons per day at this stage of the voyage. The stock of ice was itself replenished on 15 January, noted in the log as 'Watch employed watering ship'. This secured the ship's water requirements for another 20 days before the regular issue from the tanks began again on 5 February.

Terror's snow tank had been taken down on 25 March 1841 to improve ventilation on the lower deck so it is probable that *Erebus*'s snow tank had also been removed for the same reason. The snow tank's ice melting performance was poor and its role as a condenser was irrelevant while the ships were actively sailing so it is possible that the snow tanks of both ships remained in the respective ships' holds for the remainder of the expedition. The cooks would by now have been highly practiced in making water by 'thawing ice in the coppers', i.e. the boilers, so it seems a reasonable presumption that, when they switched from bulk ice melting to fill the tanks to making water for immediate use, they continued to use the same method.

Alternatively, if the snow tanks and steam pipes were still in place during this period when a daily cycle of cooking and water making in the coppers was in operation, then the daily water ration issued to the ship's complements would likely have been contaminated with lead. If this was the case then the men's blood lead would have increased but, as no sickness is recorded, apparently not enough to cause noticeable ill effects.

The Arctic 1845

The ship's cook did not have sole responsibility for food preparation. Each mess of eight men would appoint one of their number as mess-cook for the week[68] and the meals for the captain and the officers were cooked by their respective stewards. It would be particularly important for the ship's cooks on the Antarctic expedition to instruct a dependable assistant to manage the galley stove given the round-the-clock ice melting marathons which took place. Presumably this is how John Diggle, able seaman on *Erebus* during the Antarctic expedition, was able to change his job at the age of 36 to become the ship's cook on *Terror* in 1845. His presumed mentor, Richard Wall, aged 45, re-joined *Erebus* to continue his role as ship's cook.[69]

When *Erebus* and *Terror* overwintered at Beechey Island the snow tanks would have been essential for their role as condensers, but there is a reasonable probability that instead of using them to make the ships' daily water needs Wall and Diggle continued the practice of 'thawing ice in the coppers' each day as they had done in January and early February 1842. Water produced in this way would be contaminated with lead due to condensation in the steam pipe while the men's

[67] TNA, ADM 55/51, 'Erebus: Log, 1 Jan 1842 to 31 Dec 1842', pp. 3–47.

[68] Macdonald J., *Feeding Nelson's Navy - The true story of food at sea in the Georgian era*, London, Chatham Publishing, 2004, p. 100.

[69] Lloyd-Jones, R., 'The Men who Sailed With Franklin', *Polar Record*, 41(219), 2005, pp. 311–8.

provisions were boiling. The first water issued would be high in lead, with the contamination rapidly decreasing as more ice was melted. Instead of the month or so in which ice was melted for daily consumption during the Antarctic expedition, the winter quarters for the Arctic discovery ships lasted for nine months creating the potential for the ships complements to accumulate progressively higher burdens of lead over the three successive winters before the ships were deserted.

Naval routine

The variation in lead levels in the hair from Beechey Island and the bones from King William Island indicate a wide variation in the amount of lead each man received over the course of the expedition. The suggested method of water making described previously would lead to a non-uniform distribution of lead in the water issued, with the first-draw water received by those served first being much higher in lead than the water received by those lower down the order. Water being strictly rationed, its distribution to the ship's company would necessarily have been attended to with the usual naval formality. We can expect each mess being called in turn, in the same order each day.

It is notable that the levels of lead in the hair of Torrington, Hartnell, and Braine, in descending order, parallel their precedence as petty officer, able seaman, and Royal Marine. It is therefore tempting to suggest that the water may have been served out to the ship's complements in rank order, with the officers receiving more of the supposedly lead-rich first-draw water, resulting in the anomalously high death toll among the officers noted in the Victory Point record. However, in the absence of corroborating evidence that the water was distributed in this way, this suggestion must remain just one possibility among many.

Conclusion

When the ships of the Franklin expedition, *Erebus* and *Terror*, set off for the Arctic in 1845, they carried with them galley stoves fitted with water-making apparatus of a flawed design which had been hurriedly improvised in 1836. During the preceding Antarctic expedition their ship's cooks had made many tons of perfectly wholesome water by melting ice in the stoves' boilers, but when the procedure was repeated in the Arctic it is likely that the water produced was contaminated with lead. The large variation of lead observed levels between individuals may be the result of the routine for serving out the water ration, with those earlier in the sequence receiving the most lead. It to be expected that further progress in assigning identities to the recovered skeletal remains, plus the ongoing examination of the wreck of HMS *Erebus* will eventually provide definitive answers.

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Picture credits:
Figure 1. Profile plan of HMS *Terror*, 1837 with 1845 amendments, Image J1406, National Maritime Museum, Greenwich, London.
Figure 4. Artist's reconstruction of snow-tank and galley stove, Kristina Gehrmann, www.kristinagehrmann.com