Ice Regime and Ice Transport in Nares Strait

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ABSTRACT. In order to assess the part played by ice export through the Canadian Arctic Archipelago in the heat budget of the Arctic Ocean, one of the factors that must be known is the length of time per year that the channels are sealed by fast ice. To establish this for Nares Strait a series of flights was undertaken through the winters of 1970-71 and 1971-72. The resulting observations, combined with a search of historical records, suggest that the date of consolidation of ice in this channel tends to be late. A tentative calculation of annual export leads to the conclusion that the contribution of the Canadian channels may be greater than has been supposed.

RÉSUMÉ. *Régime et transport des glaces dans le détroit de Nares.* Pour évaluer la part que joue l'exportation des glaces à travers les chenaux arctiques dans le bilan thermique de l'océan Arctique, l'un des facteurs qu'il faut connaître est la longueur de la période annuelle pendant laquelle les chenaux sont bloqués par la glace fixée. Pour le constater dans le détroit de Nares, nous avons entrepris une série d'envolées pendant les hivers de 1970-1971 et 1971-1972. Nos observations, jointes à une recherche de données historiques, nous suggèrent que la date de consolidation de la glace dans ce chenal tend à être tardive. Un essai de calcul de l'exportation annuelle nous amène à conclure que la contribution des chenaux canadiens pourrait être plus grande qu'on ne l'avait supposé.

РЕЗЮМЕ. *Режим и перемещение льда в проливе Нейрес.* Чтобы оценить роль, которую играет перемещение льда через Канадский Арктический Архипелаг в тепловом балансе Северного Ледовитого Океана, необходимо знать продолжительность времени в течение года, на протяжении которого каналы оказываются закупоренными льдом. С целью выяснения этого вопроса для пролива Нейрес была организована серия полётов в зимние периоды 1970-71 и 1971-72гг. Результаты наблюдений в сочетании с исследованием исторических записей указывают на тенденцию к более позднему затвердеванию льда в этом канале. Расчёты годичного перемещения льда приводят к заключению, что вклад Канадских каналов может быть более значительным, чем ранее предполагалось.

INTRODUCTION

Estimates of ice transport out of the Arctic Ocean are quite varied, which is not surprising in view of the fact that they are based on a number of other factors, all of which are imperfectly known. These factors include current speeds in the strait between Greenland and Spitsbergen (called Fram Strait in the Russian literature, a practice which will be followed here) and in the channels of the Canadian Arctic Archipelago; the thickness and areal coverage of the ice; and the width of the area over which the transport takes place. The figures usually accepted as most reliable derive from Zubov (1948) and Gordienko and Karelin (1945) and are in the order of 3,000 km.^{3}/yr. A later estimate by Gordienko and Laktionov (1960) is considerably higher, 8,000 to 10,000 km.^{3}/yr. Coming from a source so close to that of one of the lower estimates, it should not be ignored, especially as in the meantime, in 1956, an expedition in the *Ob'* has taken oceanographic sections across Fram Strait (Balakshin 1958), the data from which

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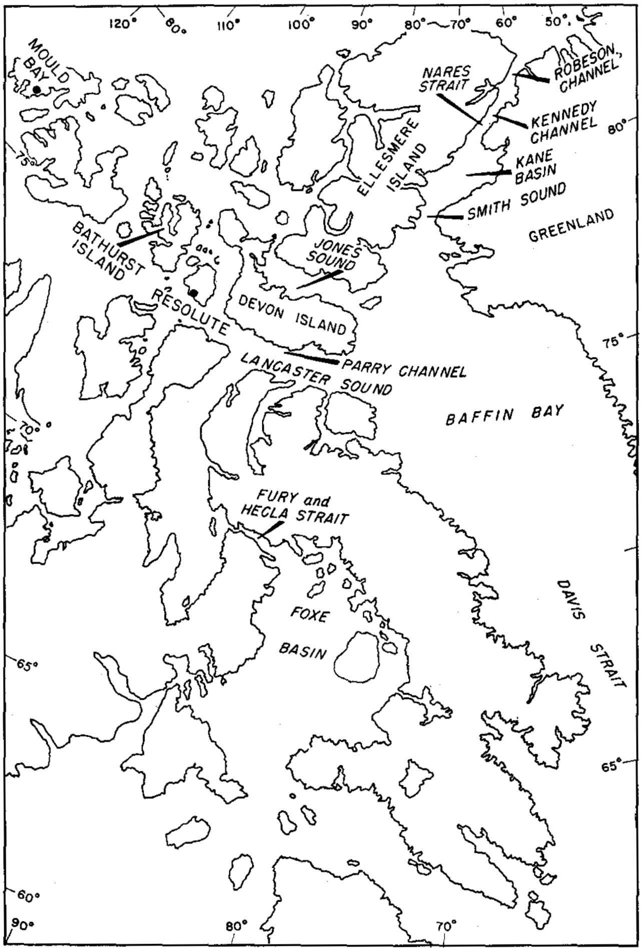

FIG. 1. The Canadian Arctic Archipelago.

unfortunately have not been published (Aagard and Coachman 1968). Vowinckel (1963) arrives independently at a figure similar to Zubov's, and an even more recent estimate, based on analysis of the barometric field in the Arctic Ocean for a 20-year period, gives an average of 2,000 km.^{3}/yr. (Antonov 1968). The only thing all sources agree on is that there are great fluctuations, both seasonally and from year to year.

Generally speaking these estimates are intended to apply to Fram Strait only, which is by far the most important export route. The Canadian Archipelago (Fig. 1) export, if mentioned at all, tends to be described as insignificant (Gordienko and Laktionov 1960). Vowinckel and Orvig (1962) give a figure for outflow through Davis Strait of 491 km.^{3}/yr. based on an ice season of 10.5 months. Most of this ice, however, must be of local origin in the Baffin Bay area. It cannot include much export from the Arctic Ocean, because the channels through the archipelago are covered for several months of the year with shorefast ice, so that transport virtually ceases. The main contribution of these channels is made in summer, when much of the ice transported through them melts in

Baffin Bay and so does not feature in the Davis Strait transport, and in the early fall and winter, before the channels consolidate. It is thus hard to establish any direct relationship between the ice transported through the Canadian channels and the outflow from Davis Strait; and no estimate of the former can be made without first establishing the length of time that the channels remain shorefast.

This involves knowing the date of break-up of the ice in the spring and also the date that the ice cover becomes complete and unmoving in the winter. The first of these dates is reasonably well documented, but records of the second are almost non-existent, except very locally from shore stations, where the observations do not usually extend far enough offshore to be significant, and from occasional accounts of ships caught in the ice. An interesting but isolated exception is described by Milne (1970). From an acoustic recording package installed on the bottom in Western Parry Channel it was found possible to distinguish between the noise generated by moving and fast ice. Results showed that after a transitional period beginning in mid-October, during which the intervals of movement became shorter and those of no movement longer, the ice finally settled into a shorefast state in late December.

To establish the date of consolidation for Nares Strait, a series of flights was made with the Northern Patrols of the Canadian Forces Maritime Command during the winters of 1970-71 and 1971-72. (For convenience Nares Strait is included under the heading of "Canadian channels" but it is, of course, international, as it separates Ellesmere Island from Greenland.) In the first year, 6 flights were made at approximately 2-week intervals between 4 December and 1 March, and in the second year 2 flights were made, on 9 January and 20 February. Owing to the prevailing darkness visual observations alone could not be relied on, so radar scope photography was used, supplemented by such visual data as could be obtained from the excellent nose position of the Argus aircraft. These helped to resolve the ambiguities inherent in the radar presentation of ice.

It is not possible to obtain detailed ice data by this method using a search radar of the type available. The radar presentation reveals only the broad contrasts — black patches which may indicate open water or very young ice, and light patches which represent more solid rough ice. These contrasts, if reliable, would have been quite adequate for the purpose, as the presence of thin ice or open water is sufficient indication of movement in the ice. Unfortunately, however, the black patches on the radar scope can also represent quite thick smooth ice, and it was for this reason that some visual confirmation was required. In the darkness just enough contrast could be detected visually to clarify the radar presentation, and with a moon to help much more detail could be distinguished.

The flights are reported fully in Dunbar (1971, 1972a). It is sufficient here to summarize the results.

WINTER 1970-71

In the winter of 1970-71 ice conditions remained unstable throughout Nares Strait, with apparently repeated opening, ridging, and refreezing, up to early or mid-February. On all flights up to this time many open or young ice patches were

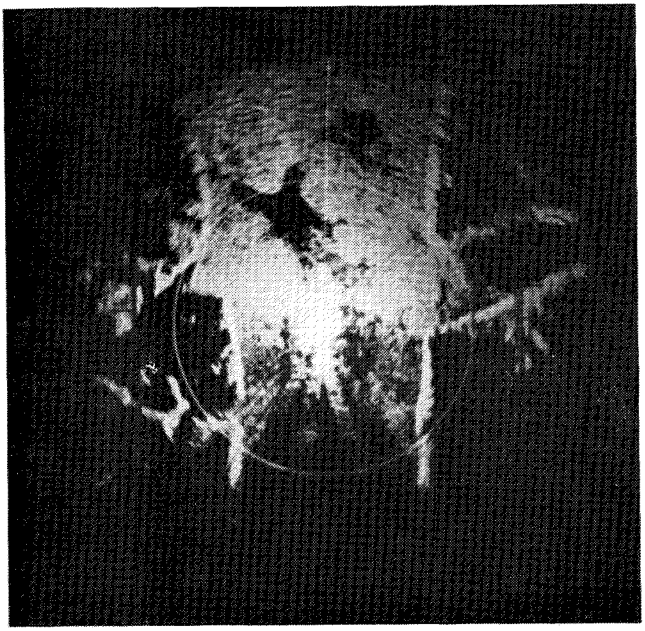

FIG. 2. Radar scope photograph of Robeson Channel on 18 December 1970, heading north (in this and all illustrations, the up-channel direction, NE, is at the top). Note the large black patches, which were open or newly frozen. Typical of the ice picture in 1970-71 up to mid-February.

seen, interspersed with very heavy old floes and areas of highly deformed first-year ice (Fig. 2). The number of open or near-open patches and recent ridging were clear evidence that movement was still going on. The greatest number of open patches were usually observed in the part of the Strait north of Kane Basin, and when consolidation came it showed first in Kane Basin, which seemed to be approaching a stable condition on 14 February. By 1 March the whole Strait from the head of Smith Sound north had ceased to move except for the north half of Robeson Channel which, however, became shorefast sometime before 1 April, when the area was next observed.

Smith Sound is the area of the North Water and has a regime all its own, remaining more or less open throughout the winter. The cause of the existence

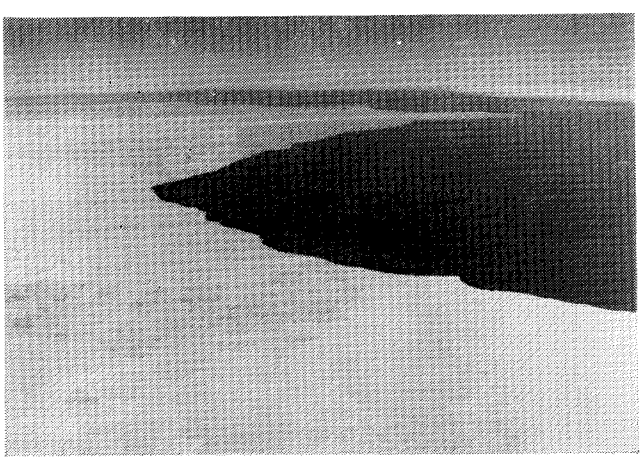

FIG. 3. The head of the North Water in June 1950, looking towards Greenland. The form and position of this ice edge varies little from year to year. Canadian Forces photo, 20,000 feet.

of this feature has been a matter of much speculation in the past (Nutt 1969), but it is now becoming clear that it is in fact a polynia of the same general character as the flaw lead normally found off the edge of the fast ice in areas of prevailing offshore winds. In this case the "shore" consists of an ice edge across the head of Smith Sound (Fig. 3). The North Water had never been systematically observed in the dark period, and therefore these flights made a significant contribution in establishing that it indeed does exist as a clearly defined phenomenon during that part of the year. It was identifiable as an area of open water and young ice on all flights, and the ice edge at its head was firmly established and unbroken by 2 February.

South of the edge there was usually an open lead, but the rest of the area consisted of young ice in concentrations varying from about 4/10 to as much as 9/10 and increasing steadily southwards in predominant age. The southern limit is difficult to pinpoint, as it consists of a gradual merging into the pack ice of Baffin Bay. In winter it seems to lie around 77° N., but the position varies considerably.

WINTER 1971-72

In the second year an attempted flight in December had to be aborted owing to aircraft unserviceability, so that the first visit to Nares Strait was on 9 January. There were many black patches on the radar presentation, but visually they were grey rather than black and far fewer than at that time the previous year. In general in fact the ice looked at least as near to stability as it was a month later in 1971. On the second flight, on 20 February, the ice appeared to be completely consolidated, and furthermore a large number of the smooth patches that had appeared on the radar photos on the first flight, and which were then grey, were easily recognizable on the radar but had now thickened to the white or first-year stage (Figs. 4 and 5). In other words, it was quite clear that there had been little or no movement since at least 9 January. This undisturbed state was reflected in the much greater proportion of smooth ice than in the previous year. Only in a few places was there ridging on the scale observed in 1970-71.

The North Water was well established and the northern edge consolidated even on the first flight. The ice south of the edge, as usual, increased gradually in predominant age southwards, from dark nilas in the north to first-year ice at the southern limit.

DISCUSSION

It is clear that as long as the ice edge at the head of the North Water remains intact, no ice from north of Smith Sound can be transported through the channel into Baffin Bay. In 1971-72 the ice edge appeared to be quite firm on both flights, and in 1970-71 it became established between 13 January and 2 February. An interesting comment here is that on the first flight, on 4 December 1970, the head of the North Water was unconsolidated, though still recognizable; on 18 December it was fully formed; but by 13 January it had broken up again. On all these flights there were old and first-year floes among the young ice in the North

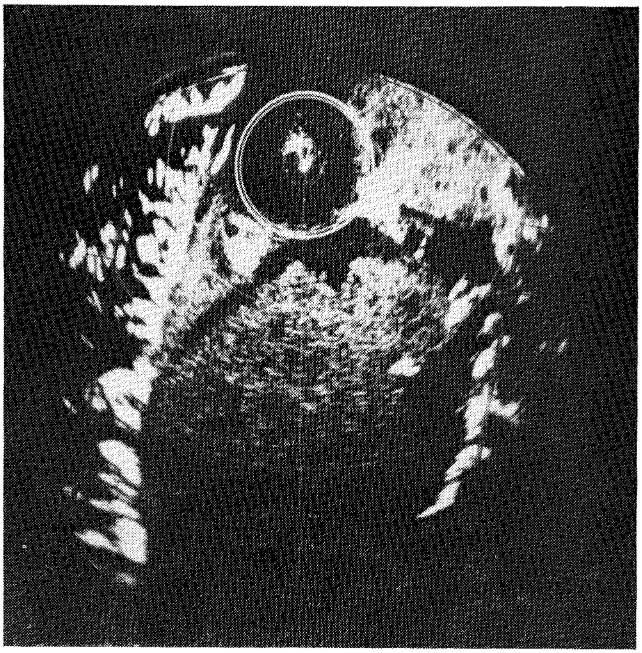

FIG. 4. Kennedy Channel on 9 January 1972, heading down-channel. Franklin Island (80° 35′N., 66° 45′W.) is just to the right of, and touching, the first (double) range ring. Note the black patch south of the island and running across to Ellesmere Island, which is part open water, part young ice. The black area to the right of Franklin Island is the radar shadow of the island.

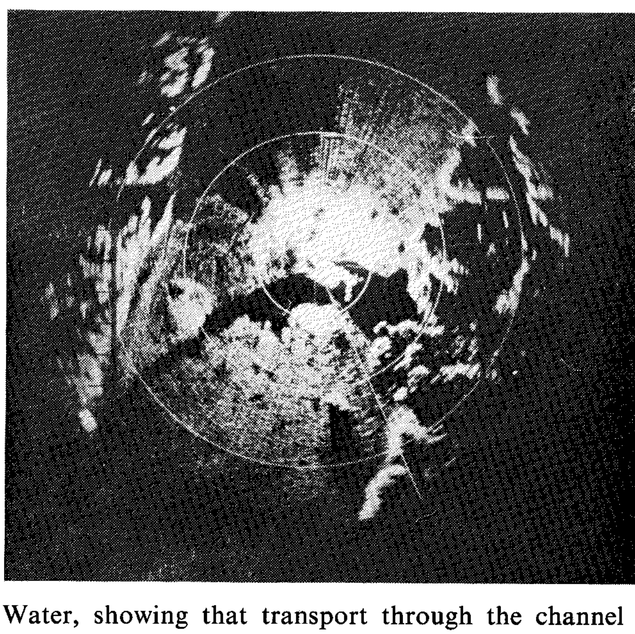

FIG. 5. The same as Fig. 4 on 20 February 1972, with the aircraft at the west end of Franklin Island. The black patch is exactly the same but the area was now covered with smooth first-year ice. A detailed comparison of the two photos will reveal other identical features in the ice pattern.

Water, showing that transport through the channel was still going on. On 2 February the ice edge was again continuous, and from this date on, and on both flights in 1971-72, only young ice was seen south of the edge. Thus it is possible to say with reasonable assurance that transport ceased in 1971 sometime in the second half of January, and in 1972 before 9 January. Any movement north of the North Water after these dates — and it went on for another month in

1971 — was merely internal movement within the Strait. It thus seems likely that the key factor in limiting the period of transport is the date of consolidation of the North Water ice edge.

Comparison with historical data

Many expeditions from 1853 on have travelled and wintered in Nares Strait, and most of these are listed in Dunbar (1971). In general their descriptions tend to reinforce the picture of an area of unstable ice, with open patches occurring throughout the winter in some areas and in some years, and with extremely large expanses of rough deformed ice. Many parties have wintered on the shores of Smith Sound and used the North Water ice edge as a means of crossing the Strait. Unfortunately this does not give us much indication of its date of consolidation, as few explorers attempted the crossing till March or later. There is, however, one record of a crossing in early December, or more accurately two crossings, one week apart (MacMillan 1918), and two in January (Peary 1903; Cook 1911).

In general, from the historical records, it would appear that 1970-71 was a fairly "normal" year for the channel as a whole, neither exceptionally early nor exceptionally late, and that in 1971-72 consolidation came rather early. For the closing of the North Water ice edge, however, the historical records give us little help.

Comparison with other areas

From the above we may make a broad preliminary assumption that transport through Nares Strait ceases sometime between 1 and 20 January, though some movement within the Strait may continue long after this. How do these dates compare with the other channels that can carry ice out of the archipelago?

By far the most important of these is Parry Channel, which communicates with Baffin Bay through Lancaster Sound and which carries at least as much and possibly more ice than Nares Strait. It was in this channel at about 112°W., that Milne's observations, already referred to, were made, giving a final closing date of late December in 1967. In 1853-54 Captain Henry Kellett with HMS *Resolute* and *Intrepid* was caught in the ice in the same area and wintered in the open channel. His ships ceased to drift on 5 November, 28 miles south-southwest of the southwest point of Bathurst Island (McDougall 1857). This is disconcertingly different from Milne's date, but on examination it proves less so than at first sight. In the first place ice conditions were generally more severe in the 1850s than in the 1960s (Dunbar, 1972b), so Kellett's date is probably anomalously early by present criteria. Secondly, he was considerably farther east than Milne's recording package, and if Parry Channel follows the same pattern as Nares Strait of consolidating first at a point where the channel is constricted, then the most likely point is to the west of Resolute, where the channel narrows and shoals and is partly obstructed by islands. This is not far from Kellett's position, where the ice may consolidate consistently earlier than at Milne's position.

There is no criterion against which to assess Milne's date except the climatic statistics, and these are inconclusive. Air temperatures at Mould Bay and Resolute (Fig. 1) were above normal in October and December of that year but well below in November. Wind data, which would be more relevant, are less easily available and have not been investigated; Milne gives the Mould Bay wind speeds for the period of his experiment, but these would have little bearing on the winds in western Parry Channel. If we assume, however, that movement ceases earlier among the islands west of Resolute than in the area of Milne's record, then perhaps it is not too far out of line to set the period within which transport may be expected to stop as sometime between late November and the middle of December.

The other two channels that carry ice out of the archipelago, Jones Sound and the exit into Foxe Basin through Fury and Hecla Strait, are even less well documented and will be arbitrarily assumed to have the same consolidation date as Parry Channel.

It thus appears that the ice in Nares Strait consolidates at least a week or two later, and possibly as much as a month or more later, than the ice in the other channels. The reason for this, which is discussed in Dunbar (1971), seems to lie in the fact that Nares Strait is an extremely stormy area, as is attested by all explorers who have visited it. Storms set in motion the large and heavy multi-year floes that are normally found in this strait at freeze-up, breaking up the younger ice and throwing it up into the tremendous ridges characteristic of the area, and leaving open patches which then refreeze. This process continues until the amount of ridged ice leaves no further room for movement, or until a period of calm allows the smooth ice to become thick enough to withstand the pressure.

This theory is borne out by the experience of the last two years (Dunbar, 1972 a). The weather charts for the two years revealed a tremendous contrast in conditions, which were extremely stormy in 1970-71 and quite calm in 1971-72 over the observation periods. This was clearly reflected in the rough ice and late consolidation of 1970-71 compared with the much smoother conditions and early consolidation in 1971-72.

Ice transport

Although the material presented here may not really warrant it, it is hard to resist the temptation to make a preliminary estimate of the amount of ice transported through Nares Strait. Given a date of cessation of through transport of between 1 and 20 January and a break-up date of mid to late July, we may assume a period of 5 to 6 months during which transport can take place. Kiilerich has measured current velocities through Smith Sound of 14 to 26 km./day (Dunbar 1951); on an annual basis these would probably be much too high, especially as on various occasions northward currents and ice movement have been observed (Nutt 1966) and there is plenty of evidence that tidal currents play an important role (Nares 1878; Bessels 1884). Furthermore, current speeds farther north in the Strait are probably lower, and it is these we must use for transport values. There are several drift records to guide us. The USS *Polaris* in 1872 was beset in the ice and drifted from 80°02 N. in northern Kane Basin to 78°21 N. in Smith Sound at an average speed of 3 km./day (Dunbar 1962). Great fluctuations in drift speed were observed by this party, as by those that followed: the highest drift speed was 26.7 km./day, the lowest almost zero, and there were many changes of direction (Bessels 1884). Greely in 1883 drifted in a launch in western Kane Basin for 13 days at an average speed of 4.6 km./day (Greely 1886). Finally, the broken pieces of the ice island WH5 drifted from Hans Island in the middle of Kennedy Channel into Baffin Bay in 1963, a journey well documented by Nutt (1966). From Hans Island to the south end of Kane Basin the pieces travelled at about 18 km./day, but there then followed a long period of inaction and aimless drift, some of it northward, so that the average speed into northern Baffin Bay was in the order of 9 km./day. All these are resultant speeds over straight line distances.

It is clear that there are considerable fluctuations in the transport. The best we can do is take a mean of the three speeds above, which is 6 km./day. Let us further assume a transport period of 5½ months or 165 days, over a width of 40 km. which is the approximate minimum width of Smith Sound, and an average ice cover over this period of 75 per cent. The average ice thickness is difficult to assess; much of the ice will be very thick and heavily ridged, but on the other hand in autumn and early winter there will be considerable quantities of thin new ice. An average figure of 2.5 m. is perhaps reasonable. These would give an annual export of 75 $km.^3$ of ice.

Returning now to the estimates of export from Fram Strait, if we accept Gordienko and Laktionov's figure of 8,000 to 10,000 $km.^3$/yr., the Nares Strait figure constitutes only 0.7 to 0.9 per cent of the total. However, if we accept 3,000 it rises to 2.5 per cent and if we take Antonov's 2,000 km^3./yr. it is 3.75 per cent. If we assume the combined contribution of Parry Channel, Jones Sound, and Fury and Hecla Strait to be twice that of Nares Strait, a not unreasonable assumption, that would raise the total export through the Canadian Archipelago to 225 $km.^3$/yr. This is about 2.5 per cent of 8,000 to 10,000, 7.5 per cent of 3,000, or 11.25 per cent of 2,000 $km.^3$/yr.

It seems therefore that if this estimate is not too exaggerated, and if the Fram Strait export is indeed 3,000 $km.^3$/yr. or less, then the ice exported through and around the Canadian Archipelago is worth considering. If, on the other hand, Gordienko and Laktionov's (1960) figure turns out to be correct, then they are perfectly justified in calling it insignificant.

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