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DESIGN STRATEGY FOR ICE NAVIGATION

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1. INTRODUCTION

Recently increasing demands for navigation to ports which are ice-infested for some part of the year are mostly due to the economical desirability of exploiting natural resources of Arctic or Subarctic regions. For this particular and simple objective the formulation of design criteria will be attempted in the following:

Consider sea transportation system between two points A and B; port A may be situated in a fiord, which is ice-infested for some part of the year, while destination point B may permit ice-free year round operation. A land fast ice cover is typical within such a fiord, while open sea-ice, i.e. more or less densily floating ice floes, normally prevail outside of the entrance to the fiord. The principal variable of the open sea ice is its extent, which changes with meteorlogic conditions, mainly the wind direction. Hence, the problem has to be solved under the following constraints:

(a) Maximum permissible draft in port A
(b) Distance from port A to port B
(c) Length of fiord at A
(d) Properties of fast ice: Time dependent statistical distribution of strength and thickness in the fiord.
(e) Statistical distribution of the distances which have to be overcome under sea ice conditions.

2. DESIGN ALTERNATIVES

Certainly, the ice-navigating vessel constitutes the "conditio sine qua non"; however, as the ice conditions vary the question arises which ice-breaking capability is most economical, because the costs of increasing it grow with higher than first order. Further, it has also been recognized that auxiliary devices may essentially improve the economy of ice-navigation; then optimal balancing of various system components becomes the problem.

2.1 Cost of Basic Icebreaker Capability

First, the cost increment for increasing icebreaking capability: Icebreaking capability is considered in three different ways [1]:

(a) The ramming capability, which is mainly determined by the mass of the vessel, i.e. its displacement,

(b) The capability of continuous operation, to which the thrust or the power on the shaft is the main contribution

(c) The coefficient of extraction, the ratio of required reverse thrust over forward thrust after ramming (basically dependent on the hull form).

Cost increments are caused by requirements (a) and (b):

(a) Increasing the displacement of the vessel is in agreement with the general economic desirability of bigger vessels. However, thicker plating and closer scantlings increase the basic costs approximately linearly with the weight.[2]

(b) Increasing the thrust is both, costly and limited: The capital cost of power capacity grows linearly; however, a bigger power plant reduces also the payload capacity approximately linearly, hence the cost increment is in first approximation proportional to the square of the increment in power capacity. Furthermore, the limitation on the propeller diameter due to the limiations of the draft determine the obtainable thrust by considering the propeller as an open turbomachine and the pressure ratios which can be produced by this type of machinery.

Icebreaking capability due to weight and power is denoted as the "basic capability"; its cost increment is at least of second power.

2.2 Auxiliary Methods

Auxiliary methods may be separated into two classes (A) shipbound devices and (B) off-ship methods.

(A) Ship-bound devices. The first three of the following shipbound devices are well known and successfully applied while methods (d), (e) and

(f) are in a development stage:

(a) Heeling tanks

(b) Mechanical pitching systems

(c) Air lubrication systems

(d) Mechanical cutting

(e) Water jet devices

(f) Steam jet devices

(B) Off-ship Auxiliary Methods

(a) Fixed installation air bubbling

(b) Explosives for blasting ridges

(c) Hovercraft as auxiliary icebreaker

(d) Barges as auxiliary icebreakers, equipped with either mechanical cutting, steam jets, water jets or blasting devices.

Principal advantage of shipbound auxiliary devices is their availability throughout the whole route; their disadvantage is their requirement of space which reduces the payload capacity of the vessel.

Off-ship devices are inexpensive only as long as they work within a contained region.

The devices listed above are only partly inter-changeable in their effects, some of them are supplementing each other, which has to be kept in mind for the following formulation of the optimization problem.

3. THE OPTIMIZATION PROBLEM

A benefit "B" derives from the contemplated transportation system within a certain time period T: Consider a payload L, the velocity of the vessel v, the probability distribution p(t,s) of the ice resistance (usually the varying mechanical properties are scaled on the thickness h of a "standard ice" which is then comtemplated); the velocity depends on p and hence on h, hence, v = v(h). The expected benefit is found as

$$E\{B\} = u.L.T.E\{v\} \qquad \ldots\ldots(1)$$

where "u" denotes the unit costs, i.e. for instance the transportation cost per ton and mile while E{v} is defined as

$$E\{v\} \equiv \iint_{ts} v[h(t,s)]\, p(t,s)dt,ds \qquad ......(2)$$

In the following indices "1" or "2" denote reference to the hull or to the propulsion system respectively, while higher indices refer to auxiliary devices. The operating costs, denoted $\bar{\bar{c}}$ vary to some extent statistically; further, by k_1 and k_2 respective fractional cost increments for corresponding ice-strengthening are denoted while costs of auxiliary devices are assumed to vary only neglegibly.

The expected total costs c_+ are then composed of

$$E\{c_+\} = \sum_{i=1}^{2} \bar{c}_i(1 + k_i) + \sum_{i=3}^{n} \bar{c}_i + E\{\bar{\bar{c}}_2(1 + k_2^*)$$
$$+ \sum_{i=3}^{n} E\{\bar{\bar{c}}_i\} \qquad ......(3)$$

By equating costs and benefit the unit costs are obtained as

$$u = \frac{E\{C_+\}}{L.T.E.\ \{v\}} \qquad ......(4)$$

which should be minimized.

The payload L in equation (4) depends also on the sizes of the propulsion engine and of the auxiliary equipment on board, hence

$$L = L_o(1 - \sum_{i=2}^{n} \lambda_i k_i) \qquad ......(5)$$

where λ_i constitute constant factors. The objective function of the optimization problem is then found by substituting equation (5) into equation (4). The constraints are then as follows:

The velocity

$$v = v_o[1 - v_1(f)p_1'(s,t,f) - v_2(h)p(s,t,h) +$$
$$\sum_{i=}^{n} \varepsilon_i k_i v_i(v_1, v_2)] \qquad ......(6a)$$

where the notations are used:

v_o = velocity on open water
v_1 = velocity in sea ice
v_2 = velocity in fast ice
p_1 = probability density of ice floes
p_2 = probability density of fast ice of thickness 'h'
ε_i = factors of proportionality
v_i = velocity increment due to auxiliary device

Further constraints are

$$k_1 > 0 \quad k_2 > 0$$
$$k_3 \geq 0, \; \ldots\ldots \; k_n \geq 0 \qquad \ldots\ldots \text{(6b)}$$

Semi-empirical functions or analytical expressions for the velocities v_i may be substituted in equation (6a) and subsequently the optimization problem can be solved numerically.

4. A SIMPLIFIED PROBLEM

Consider a fast ice cover of standard ice of random thickness. The probability distribution of the thickness is stationary in time and also space invariant. An icebreaking vessel commutes between two points and the ice cover reforms completely such that the statistical properties of the refrozen track are equal to the properties of the undisturbed field.

Although these assumptions are quite artificial they exhibit already the basic elements of the problem. Further simplifying assumptions may be made with regard to the equipment. The speed of operation under basic icebreaking capability is constant and denoted by v_1; as well as the velocity when the auxiliary device is deployed which is denoted by v_2 with

$$v_2 = \mu v_1 \qquad \ldots\ldots(7)$$

and $0 < \mu < 1$

Standard ice up to the thickness h_i may be broken by basic icebreaking capability and for ice-thicknesses $h_1 \leq h \leq h_u$ an auxiliary device may be deployed. We postulate further that the coast of increasing the basic icebreaking capability increases with the 2nd power of the thickness "h", while the cost u^* (equ. 4) may be written as follows (considering capital service only):

$$u^* = \frac{C_o[1+k_a(h_u-h_i) + k_b \cdot h^2]}{v_1 \quad P\{h \leq h_i\} + v_2 P\{h_i < h \leq h_u\}} \qquad \ldots\ldots(8)$$

where $\{h \leq h_i\}$ denotes the probability of the thickness of h being less than h_i; Many probability distributions can be made to fit certain data; for this particular example here an exponential distribution is selected which may be justified from one particular histogram of measurements taken last spring on Lake Melville (sec Fig. 1).[3]

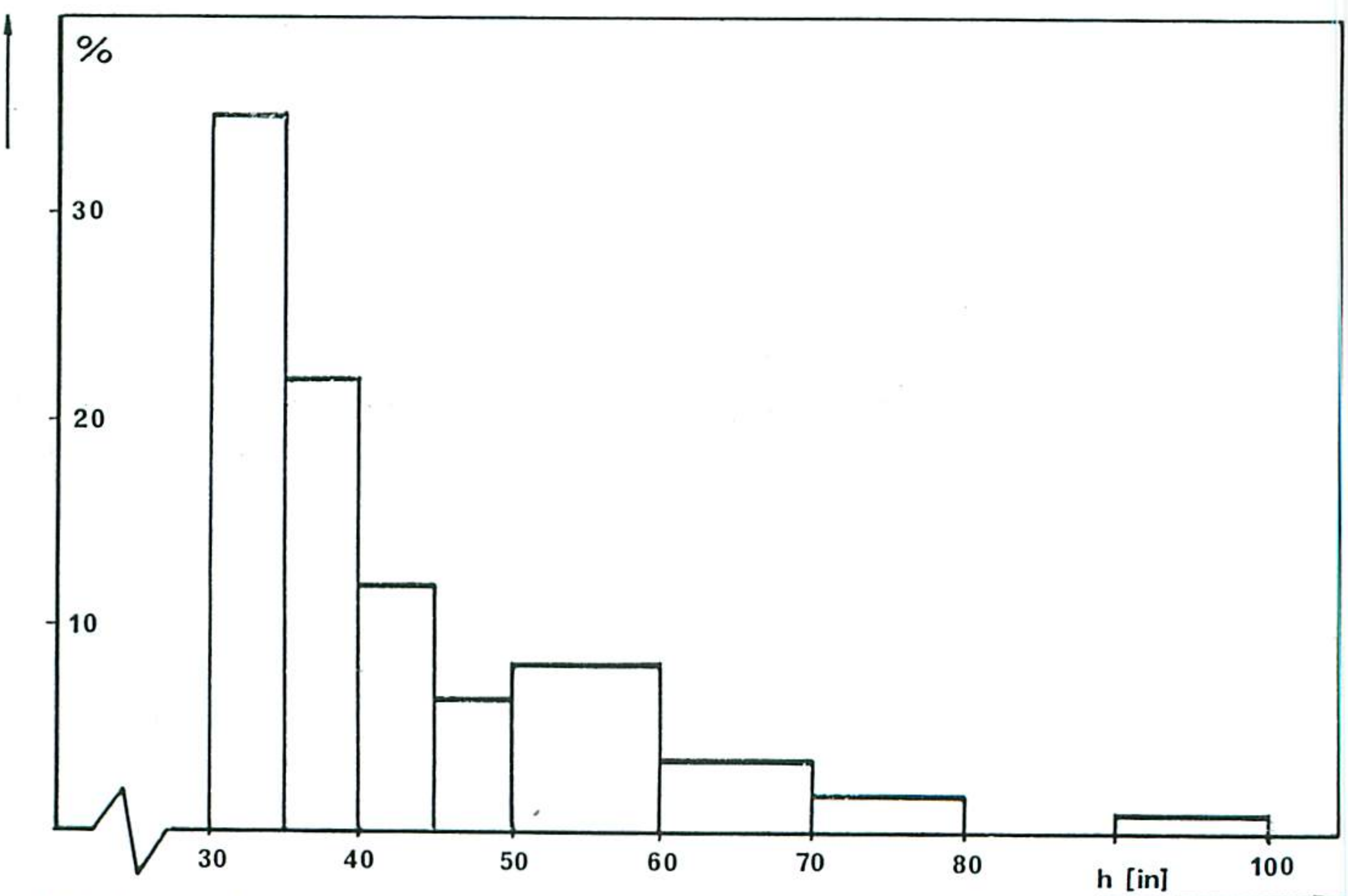

FIG. 1 Histogram of ice-thickness measurements at Lake Melville (Spring 1973, see ref. [3])

Mean and variance of the thickness measurements may be $\bar{h}$ and σ^2, hence the probability density in this example is

$$p(h) = \frac{1}{\sigma} \ell^{-\frac{h-(\bar{h}-\sigma)}{\sigma}} \qquad \text{for } h \geq \bar{h} - \sigma \qquad \ldots\ldots(9)$$

$$\text{and } p(h) \equiv 0 \qquad h < \bar{h} - \sigma$$

Substituting equation (9) and (7) into equation (8) yields:

$$u^* = \frac{\bar{c}_o[1+k_a\ (h_u - h_i) + k_b h_i^{\,2}]}{v_1[1-e^{(m+1)}+\mu(e^{-(m+1)}-e^{-(n+1)})]} \qquad \ldots\ldots(10)$$

with m and n denoting a scaling of the thickness "h" by means of its variance:

$$m + 1 = \frac{h_i - \bar{h} + \sigma}{\sigma} \qquad \ldots\ldots$$

$$(11)$$

$$n + 1 = \frac{h_u - h + \sigma}{\sigma} \qquad \ldots\ldots$$

Heuristically it is obvious that equation (10) must have a minimum. With the parameters of

μ = 0.5, 0.3 and 0.1

k_a = 0.05

k_b = 0.25

$\bar{h}$ = 3 ft.

σ = 2 ft.

a graph of equation (10) is plotted in Figure 2. A numerical solution of the minimum problem is also easily worked out.

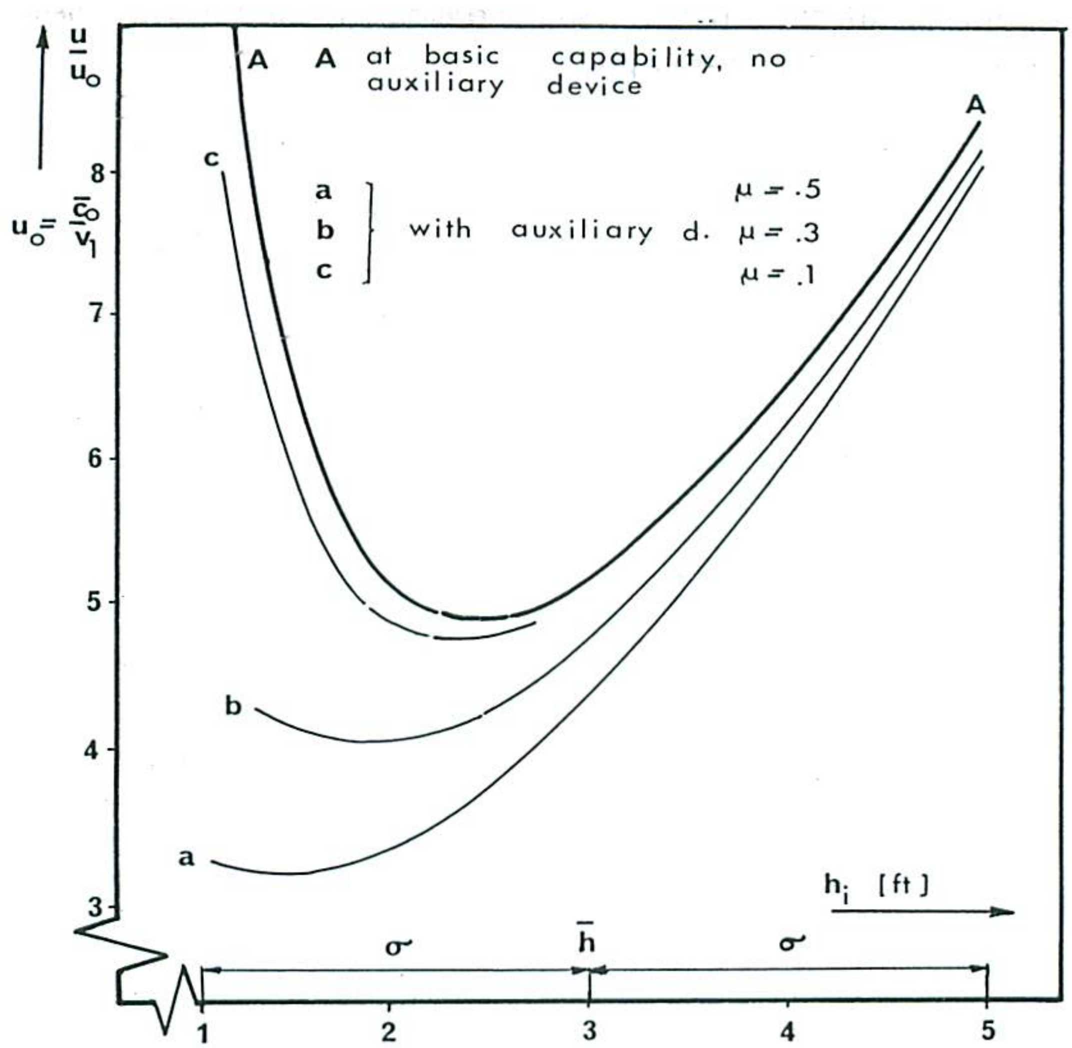

FIG. 2 Ratio of unit costs of icenavigation as a function of the design thickness h_i for basic icebreaking capability

The results of Figure 2 indicate a significant reduction of the unit costs of transportation due to a linear auxiliary device. In case the rate of progress when deploying the auxiliary device is one half of the normal progress the reduction under the above assumptions are 40% when comparing optimal conditions.

5. DISCUSSION OF AUXILIARY DEVICES

In the following some auxiliary devices are compared on the basis of their operating costs which may be easily obtained by means of an energy balance. A detailed optimization study would certainly require capital costs, expected time of operation, component lifetime, etc.; however, these data are either not easily accessible or not available yet. It is also reasonable to distinguish devices and methods which do already exist and have been tested from those under development at the present time. To the first group belong heeling tanks in bubbling systems along the hull and mechnaically induced pitching motions. For comparing these methods in detail it may be referred to the pertinent literature. To the latter group belong the mechanical ice cutter[4,5] and blasting devices (on push barges)[6] which are both presently tested by the U.S. Coast Guard; further belonging to this group are water jet [7,8] and steam jet devices. Incidently, these methods would be classed into the same groups if the classification were according to their effects: The improvements of the first group relate mainly to a reduction of the friction losses along the hull (for pitching and heeling there are also some additional downward forces due to angular accelerations), the second group relates to actions on the ice in front of the vessel.

With respect to the costs of operation the costs of energy are the decisive criterion; as all of it derives from some internal combustion process of fossil fuel the required energy divided by the efficiency of conversion constitutes a valid measure. Therefore, the efficiency of conversion are listed in the following:

(a) <u>Heeling tanks (η_H):</u>

Assuming direct diesel driven water pumps with $\eta_{diesel} = 0.40$ and $\eta_{pump} = 0.7$ the with $\eta_{pump} = 0.7$ the efficiency η_H is obtained as:

$$\eta_H = \eta_{diesel} \cdot \eta_{pump}$$

$$\eta_H = 0.28$$

(b) <u>Mechanical pitching system(η_p):</u>

The energy losses of this system are rather small, in the first approximation $\eta_p = \eta_{diesel}$,

hence $\eta_p = 0.40$

(c) Air Bubbling(η_A):

Assuming a diesel driven radial compressor ($\eta_{compressor}$ = 0.7)

$\eta_A = \eta_{diesel} \cdot \eta_{compressor}$

$\eta_A = 0.28$

(d) Mechanical Cutting (η_{MIC}):

In case of a diesel electric drive with electric conversion efficiencies $\eta_{Generator} = 0.9$ and $\eta_{Motor} = 0.9$ the efficiency of mechanical ice cutting becomes

$\eta_{MIC} = \eta_{diesel} \cdot \eta_{generator} \cdot \eta_{motor}$

hence $\eta_{MIC} = 0.32$

(e) High Pressure Water Jets (η_j):

The efficiency η_{Pist} of a high pressure piston compressor of 4 cascades does not exceed 65 per cent, hence η_j in case of a directly diesel driven piston compressor is

$\eta_j = \eta_{Pist}$

hence $\eta_j = 0.26$

(f) Low Pressure Steam (η_s)

The efficiency of steam generators is slightly higher than 80 percent, hence $\eta_s \equiv \eta_{boiler}$

$\eta_s \equiv 0.8$

(g) Underwater blasting (η_B):

Propane and compressed air are injected under the ice cover, this mixture is then blasted off. The efficiency of the air compression alone is (according (c) $\eta_B = 0.28$

The power requirements of methods (a) and (b) relates clearly to the mass of the vessel while method (c) air bubbling correlates to a linear dimension, the length of the water line. Hence, by considering the other cost elements as space requirement, average period of operation, capital costs, etc. a "trade off" point can be determined above which air bubbling is economically superior to heeling and pitching.

Methods (d) mechanical ice cutting, (e) high pressure water jets and (f) low pressure steam jets can be directly compared. High pressure water jets in front of the bow have been proposed first by A. Pesharskii[4]: later on a U.S. patent has been granted to D. Bennett of Sun Oil Co.[8]. As to this author's information and experience the method is unlikely to succeed for the following reason:

Generating high pressure jets requires a rather rigid device. As due to random irregularities of the ice surface and due to pitching motions of the vessel the distance between the nozzles and the ice surface varies; this distance has to be kept big enough to prevent damage. However, the turbulent decay of the liquid jet increases exponentially with the distance and hence the effect of the jet decreases.

Therefore, the prospects of steam jets and of mechanical ice cutting need only be compared:

Allowance has to be made for both, that mechanical energy is by the factor η_{Boiler}/η_{MIC} = 2.5 more expensive than steam, while on the other hand the requirement of mechanical energy E_C is only 1/10 of the energy required for melting; however, low grade steam can be easily generated out of waste heat at no operating costs. Denoting by E_B the energy production of a supplementary boiler, by E_W the utilized waste energy and by E_C the mechanical energy required for cutting ice the following two inequalities

$$E_B \leq 2.5\ E_C \qquad \text{...............(12a)}$$

the economic condition, and

$$E_W + E_B \geq 10E_C \qquad \text{...............(12b)}$$

the energy conditions are established, where steam erosion compares favorably with mechanical cutting. It follows immediately that the capacity E_B of a supplementary boiler should not exceed one third of the waste heat utilization.

$$E_B \leq E_W \qquad \text{...............(13)}$$

Further, by denoting the energy at the shaft of the propeller by E_s and assuming that the obtained waste energy is

$$E_w = \frac{3}{2}(E_s + E_c) \qquad \text{.................(14)}$$

(which is a rather inefficient heat exchange) it is easily obtained by substituting equation (14) into inequality (12b) that steam ice eroding can be expected to be superior to mechanical ice cutting MIC if the power ratio of the MIC

$$E_c/E_s < 0.25 \qquad \text{.................(15)}$$

If $E_c/E_s < \frac{3}{17}$ then waste heat utilization alone is more favorable, above that ratio a supplementary boiler is necessary.

By considering the capital costs and adaptability for a variety of operations (as for instance the steam jet method can cut deeper slits, the hardware is less susceptible to mechanical damage, the method can be utilized for improving the extraction properties when the vessel is ramming and to some extent the method seems also promising for navigation in disintegrating slush) by considering the above features the balance shifts further in favor of the steam jets.

Underwater blasting (submerged Ice Cracking Engine = SUBICE), a proposal brought forward by the Southwest Research Institute is anticipated as a push barge with a modified Alexbow by which a mixture of high pressure air and propane is released. According to ref. [6] the power requirement of the compressor above for obtaining the compressed air is already higher than the power requirement of the MIC. Further, the method is bound to fail at ridges, because fracture occurs then on the weakest place leaving the ridge virtually undisturbed. In predominantly salt water ice this method might even be hazardous.

A hovercraft has been successfully tested by Sun Oil Co. for clearing a channel in 3 ft. thick ice[9]. The gross weight of the hovercraft was 280 tons, the dimensions were 57 x 75 sq. ft. Hence, some dynamic effect is seemingly inducing fracture, because the static load will not explain it. Whether the method is already capable of negotiating barriers as caused by ice ridges is not known yet.

5. CONCLUSION

The formulation of the general problem of cost optimizing ice transportation has been presented. A simplified example was used to demonstrate the importance of proper balancing of basic icebreaking capability versus auxiliary equipment with respect to the statistical properties of ice-conditions. Auxiliary equipment was then discussed, with respect to costs and variety of application it has been concluded that a low pressure steam jet device is likely to be most promising proposition at the present time.

6. ACKNOWLEDGEMENTS

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