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PRELIMINARY OBSERVATIONS ON LOOSE WOOL FELTING TOGETHER WITH ITS FOLLOW-UP STUDY

MUHAMMAD ASHRAF ALI

PCSIR Laboratories, Rajshahi

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Certain inrtoductory studies indicate that the positions of the jars on a laboratory felting machine, the viscosity and volume of the felting medium largely affect loose wool felting rates which appear to be also influenced by an interaction between fibre type and the liquor volume. These effects primarily suggest the paramount role of the variations in compressive forces on the wool assemblies. A further comparison employing two distinct estimators of loose wool felting rates seems to substantiate the trade opinion vis-a-vis the significance of fibre thickness and elasticity. Eventually, the variations of felting rates along the line of woollen manufacture signify some difficuity of predicting the felting shrinkage from observations at the preceding stages of processing.

Felting is the phenomenon of irreversible entanglement. It is generally caused by the response of an assembly of wool fibres in aqueous mediums of suitable pH, temperature and viscosity, to any external agencies that induce bulk compression leading to a series of discrete rootward fibre migrations. The migration, usually controlled by a ratchet mechanism due to the scale structure, brings about a change of the assembly dimensions. Indeed, the dimensional changes of fabrics due to felting shrinkage are the most complex problems of the wool industry. Since raw wools differ widely in felting propensity, it is desirable to impart varying degrees of shrink-resist treatment depending on their actual felting properties, preferably, at an early stage of manufacture. In addition, a knowledge of loose wool felting rates seems valuable to reduce the fibre breakage in carding, the resulting noil extraction in combing and the loss of yarn strength, if the scouring conditions are adjusted to minimise the irreversible entanglement of diverse wools. For these reasons, some ambient factors which are likely to affect loose wool felting rates have been examined here with extreme wool types.

The forecasting of felting shrinkage from observations at the previous stages of processing, although roughly possible in a very small range of fibre characteristics[1,2] is generally complicated in a wide range of wools commonly met in practical situations.[3,4] This disagreement is probably attributable to differential changes[5,6] of the relevant fibre properties. A further error of the prognosis may arise from the dissimilar measurements of felting rate, which are frequently used to study linear assemblies such as carded sliver, combed top, yarn and fabric derived from the same wool. For example, the felting rate of loose wool has been exhaustively estimated by the density of the felt,[2,3,7-9] whereas the felting of top[1] and yarn [10,11] is usually given by percentage linear contraction and of fabrics, by area shrinkgae.[12,13] In addition, the mean displacement of the fibres could be used as an index of fabric felting.[14-16] In order to gain further understanding of this problem of linear comparisons, a rather new parameter has been examined to decipher its suitability as an index of loose wool felting rates.

Experimental

Loose Wool Samples.—Extraneous influences on the felting rate were studied with commercially scoured hand-carded samples of merino 64^s and Hampshire wools. However, a comparison between two distinct measurements of felting rate was made with data on 24 raw wools and 22 processed wool assemblies. The former comprised random samples of 8 carpet wools covering the available range of the Pakistani varieties and 16 wools representing the Australian types. They were washed in a 0.02% Nonidet (P40. Shell Chemicals) solution, air-dried and hand-carded. Besides, the samples of processed wools were drawn from the slubbings, slivers, tops and noils of merino 64^s, Southdown, Ryeland and Border Leicester wools of the Australian series. The rovings of Merino, Ryeland and Border Leicester wools, before and after their treatment with hot water to minimise fibre crimps, were unravelled and hand-carded for drawing additional samples. The succeeding tests were generally carried out at 65% r.h. and 21°C.

Initial Specific Volume in Compression Testing.—From each sample a specimen of 1 g wool was placed inside a metal cylinder of internal dia 3.48 cm and depth 7.55 cm. It was compressed and decompressed twice to a fixed volume of 10 cm^3 by means of a rigid piston of dia 3.45 cm attached to the cross-head of an Instron tensile tester (model TT-BM) traversing at the rate of 2 cm/min. During this cyclic compression the recorder chart moving at the rate of 5 cm/min registered both the specific compressional load and height of the wool assembly. Its initial height was then noted from the relative position of the piston just at the point of zero load on the assembly in order to obtain the specific volume, V_i. This procedure reduced differences in the initial packing of the wools[17] and gave a value of the specific volume which was largely determined by the elastic properties[18] of the fibres. For satisfactory reproducibility of the results, at least 3 specimens of each sample were studied for V_i and were then subjected to the felting test separately.

Loose Wool Felting.—A specimen of 1 g wool was generally submerged in 35 ml solution of 0.1N HCl admixed with a drop of wetting agent inside a 110-ml cylindrical jar (of height 7.5 cm and external dia 5.0 cm) fitted up with watertight lid. It was then fixed to one of the 6 positions on a shaking-type machine (of 150 rev/min) which was somewhat similar to those used in Aachener Filtz test.[2,3,7–9] Unless stated otherwise, the possible variations due to jar and position were controlled by employing the same order of jar and position in every test. The usual shaking for 1 hr produced felt balls which were air-dried. The 3 orthogonal dia d_1, d_2 and d_3 (generally along the major and minor axes in case of an ellipsoidal shape) of a felt ball were estimated at a magnification of 10× in order to obtain their arithmetic mean d and geometric mean $\sqrt[3]{d_1 d_2 d_3}$. The felting rates were also estimated by the parameters D_f and F defined below.

$$D_f = \frac{1}{V_f} \tag{1}$$

where $V_f = \frac{1}{6}\pi\, d_1 . d_2 . d_3$ and,

$$F^{[19]} = \frac{V_i - V_f}{V_i} \times 100 = \frac{D_f - D_i}{D_f} \times 100 \tag{2}$$

where $D_i = 1/V_i$. According to the usual conventions of textile science the assembly density D of equation 2 may be substituted by (i) volume or density of a random fibre assembly, (ii) linear density or mass per unit length of top and yarn, and (iii) surface density or mass per unit area of fabrics, to show that the equation is also equivalent to the expressions for percentage length or area shrinkages due to felting. Finally, the desirability of using the sundry estimators of loose wool felting rate seems warranted by a further insight that they provide into the problem as indicated succeedingly.

Manufacture of Woollen Yarns and Fabrics, and their Shrink-proofing.—The Merino 64s and Southdown wools were carded with a fine woollen card, and the Border Leicester and Ryeland wools, by a coarse card. All of them were separately spun on a ring frame to produce singles of 200 tex and 2.4 turns/cm. After ageing for 2 yr, a portion of each yarn was shrink-resisted at 40°C with 4% $KMnO_4$ (on the weight of wool) in a saturated solution of NaCl.[20] With each of the treated and untreated yarns of the 4 wools duplicate samples of cloth (5″×5″) were manually plain-knitted using two opposite runs in order to minimise any variations due to patterning. The stitch consisted of 1 cm loop length, 4 courses and 4 wales per cm each.

Yarn and Fabric Washing.—The woollen yarns and fabrics were relaxed in distilled water at 60°C for 2 hr and air-dried. From each yarn at least 10 specimens of individual length nearly 25 cm were measured out under a tension of 20 g and separately enclosed inside a Terylene tube.[19] Furthermore, the area of a relaxed cloth specimen was obtained from six observations on both surfaces held under a pressure of 3 g/cm². The cloth and yarn specimens were soaked together in a 0.2% soap–soda solution at 21°C and then washed together in 1:20 (w/w) wool–liquor with the aid of 1600 hand-squeezings. After the washing, the felted yarns were carefully freed from their envelopes. Also, the felted length and area were estimated as before, the shrinkages being expressed as the percentages of their respective measurements after the wet-relaxation.

Results and Discussion

Viscosity.—The role of liquor viscosity, if significant in governing the felting rate of loose wool, could provide valuable information for adjusting the scouring processes. Hence, this variable was briefly studied, always using the same arrangement of the 6 jar-positions in every test, with Merino 64s sliver in 40 ml sucrose solutions of varying concentration giving rise to 1, 2, 3, 6 and 15 centipoise viscosities at 21°C. The results, when subjected to an analysis of variance, showed a highly significant viscosity effect as illustrated in Fig. 1. The observed viscous drag on fibre movement, although not directly comparable, is likely to prevail upon fabric felting,[21] but it appears to be a secondary factor relative to the strong effect of $CaCl_2$ in solution,[22,23] a well-known cause of hardness of water. However, the difficulty of producing measurable felt balls obviously prohibited any effort to widen the observed range of viscosity, but the probable sources of scattering in the observations (Fig. 1) have been examined for the progressive refinement of successive comparisons.

Conditioning, Jar and Position.—Although the effects of conditioning (presoaking) time,[24] jar and position[7,24] of the felting machine had been studied with the high-felting merino wools only, these factors are yet to be examined at very low felting rates for warranting a rigorous comparison of the extreme wool types. For this reason, a poor felting Hampshire wool was tested in an adverse felting condition as with 70 ml liquor volume. The volume of the felt ball thus obtained was nearly 32 ml which contrasts well with the corresponding

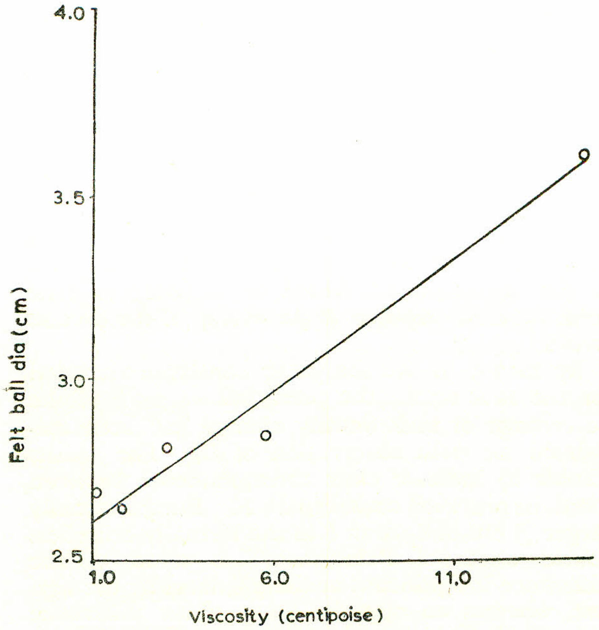

Fig 1.— Relation between felt ball diameter (*d*) and viscosity of the felting solution.

value (usually 18 ml) of high felting wools. The 6 jars and 6 positions were properly identified to arrange them according to a Latin square design[25] incorporating the 6 conditioning periods of 0, 10, 20, 40, 60 and 1440 min. The experiments were undertaken in randon fashion to minimise any pattern effect. The results (Table 1) of the analysis of variance on the felt ball volume (an inverse index of felting rate) are in harmony with those obtained for the Merino wools.[7,24] The nonsignificant conditioning effect, as noted on yarn felting rate[26] even with extreme wools,[27] may imply a predominant role of fibre surface structure rather than substance differences. But the significance of the position and jar effects appears to suggest considerable variations of compressive forces involved therein. Besides, the position effects were analysed by Duncan's multiple range test to sort out only 3 positions (for the subsequent testing) which gave (a) reasonably highfelting rates, (b) felt balls of similar diameter and (c) shape; the positions givingt he minimum coefficient of variation of felt ball volume fulfilled the last stipulation.

TABLE 1.—ANALYSIS OF VARIANCE ASSOCIATED WITH THE INDICATED VARIABLES AT A VERY LOW FELTING RATE OF A HAMPSHIRE WOOL.

Sources of variation	Sum of squares	Degrees of freedom	Mean square	*F* value
Conditioning time	11.54	5	2.31	1.75
Jar	26.01	5	5.20	3.94*
Position	51.91	5	10.38	7.86**
Error	26.41	20	1.32	
Total	115.87	35		

* and ** respectively denote significance at the 5% and 1% levels.

TABLE 2.—COMPARISON OF THE OBSERVED PERCENTAGE OF BULK DENSITY CHANGE *F* WITH ITS PREDICTED VALUE $\hat{F}$ AND THE INITIAL SPECIFIC VOLUME *Vi* OF THE 8 PAKISTANI AND 16 AUSTRALIAN RAW WOOLS.

Sample	*F* (%)	$\hat{F}$ (%)	$\hat{F}$—*F*	*Vi* (cm3)
Kail	85.7	85.3	—0.4	36.29
Kaghani	86.3	86.9	0.6	34.48
Beluchi	85.8	86.9	1.1	33.14
Rakhshani	87.8	89.5	1.7	32.95
Hashtnagari	83.4	83.9	0.5	34.00
Peshawari	84.8	85.3	0.5	33.90
Damani	83.0	83.4	0.4	34.48
Buchi	87.5	88.1	0.6	34.95
Merino A	86.8	85.5	—1.3	38.95
Merino B	88.1	87.3	—0.8	38.57
Merino C (Coarse)	85.7	86.7	1.0	33.33
Merino D (Coarse)	84.2	84.9	0.7	33.33
Merino E	85.6	84.5	—1.1	37.62
Merino F	80.5	79.6	—0.9	38.00
Merino G	83.7	82.6	—1.1	37.62
Merino H	82.9	82.8	—0.1	38.95
Southdown	68.9	72.1	3.2	39.81
Ryeland	77.2	76.9	—0.3	38.95
Suffolk	76.7	77.8	1.1	36.00
Shropshire	77.2	77.1	—0.1	38.57
Dorset Horn	77.2	76.7	—0.5	39.43
Romney	83.6	84.9	1.3	32.19
B. Leicester	83.3	83.9	0.6	33.90
Crossbred	80.2	78.9	—1.3	39.43

The coefficient of correlation between *F* and *Vi* (r=—0.516** is significant at 1% level.

Liquor Volume.—In view of the foregoing stipulations, a small range of felting liquor, varying from 18 to 63% of the jar volume, was studied for its volume effect on the felting rates of Merino 64^s (fine). Ryeland (medium) and Border Leicester (long) slubbings. This analysis, designed to ascertain an appropriate wool: liquor: jar ratio for a cross-sectional study of felting rates, seems highly desirable even though early work[24] with only fine wool showed the significance of wool: liquor ratio. In conformity with the early observation, the results (Fig. 2) generally suggest an inverse relation between the diameter of felt ball and wool: liquor ratio, thereby, implying a direct relation between felting rate and the ratio. The relation is also linear except in case of the Border Leicester slubbing, when it is felted in a large volume of the liquor, which obviously produces a low force of bulk compression in a given volume of the jar. The observed deviation from linearity is at least 1 mm whilst its standard error of measurement is nearly $0.1\sqrt{3}$ mm. Hence, the deviation is highly significant and is paralleled by the fact that among the 3 wools, Ryeland slubbing of

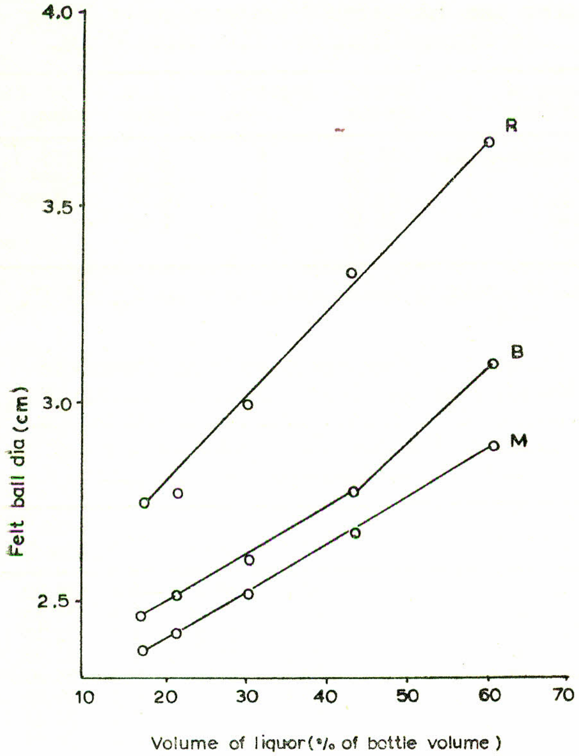

Fig. 2.—Relation between liquor volume and felt ball diameter ($\sqrt[3]{d_1 d_2 d_3}$) of the slubbings of Merino (M), Ryelaed (R) and Border Leicester (B) wool; bottle denotes the jar.

fairly large fibre dimensions shows (Table 4) the highest specific resistance to bulk compression, whilst the Border Leicester slubbing recorded the greatest force of both the with- and against-scale friction.[27] Consequently, in the light of the work[28] on fibre movement under the influence of applied force, it is suggested that the critical point of the noted interaction may occur when the superincumbent compressive force tends to be equal to the antiscale frictional force of the fibre under investigation. However, any proportion of wool: liquor: jar volumes given by the parallel portion of the graphs i.e. before the critical point of interaction shown in Fig. 2, preferably the midpoint, could be suitable for cross-sectional comparisons of the felting rates as given below.

Comparisons of the Two Estimates of Loose Wool Felting Rates.—A graphical analysis of the two measures D_f and F showed a good fit over the entire range of felting rates exhibited by 24 raw and 22 processed wool assemblies. The relation between F and D_f was generally curvilinear but it could be considered linear in a very small range. A further analysis revealed a good linear relation between log F and log D_f. This is best described by equation 3 which also defines the least square estimator, F (of F) as follows:

$$F = \mathrm{A}\,(D_f)^{\mathrm{B}} \tag{3}$$

where the constants A and B can be evaluated from a regression of log F on log D_f (expressed in g/100 cm^3). For example, the 46 observations of the pooled sample gave A=25.8 and B=0.407 whereupon D_f accounted for 70.7% of the variations of F. But in the sample of 24 raw wools, wherein D_f accounted for 86.2% of the variations of F, A=48.2 and B=0.193. This difference in the variations accounted for is likely to arise from variable response to processing of the diverse wools.

By means of the foregoing constants recorded for the raw wools, the predicted value $\hat{F}$ of the percentage of bulk density change has been calculated for each observation of $D_{\hat{F}}$ The results (Table 2) indicate close correspondence between F and its observed counterpart, F. But $\hat{F}$ is usually larger (7 out of 8) than F in the virtually crimpless coarse wools of Pakistan. This trend of the difference is significant at the 4% level by the sign test, whereas an opposite sense of the difference (10 out of 16) observed in the Australian wools, is nonsignificant. This is due to a few coarse wools of the latter, irrespective of their wide differences in crimp levels, usually possess a higher value of F as in the Pakistani wools. These opposing trends of the difference $F-\hat{F}$ as manifested by the coarse and fine wool groups are definitely indicative of a strong effect of fibre diameter which is likely to overwhelm the well-known crimp effect on felting rate. This inference, though at variance with an early generalisation of the crimp effect being more important than the diameter effect,[27'29] is in conformity with trade opinion.[30] Furthermore, the highly significant correlation between F and V_i ($r=-0.516^{**}$) seems to corroborate the effect of fibre elasticity on felting rate.[30] But the correlation appears to contradict an inference (based on felt-density considerations)[31] that the loose wool felting rate is quite independent of the initial fibre dispersion, because V_i is a direct measure of the fibre dispersion. However, the estimation of F, in practice, is rather difficult although it is likely to represent the felting rate better than D_f.

A Follow-up of the Felting Rates.—A distribution of the felting behaviour displayed by the 4 widely different wools along the line of their woollen processing from raw wool upto the shrink-resisted fabric is set out in Table 3. An inspection of the data reveals a high correlation between the raw wool and slubbing felting rates of the 4 breeds. Besides, the values of both F and D_f in the slubbings are slightly lower than their respective values in the raw wools. The low felting rates of the slubbings together with their reduced specific resistance to bulk compression (Table 4) seem rather strange when they are considered in thelight of the well

TABLE 3.—VARIATION OF THE FELTING RATES WITH WOOLLEN PROCESSING OF THE 4 WOOL TYPE.

Sample	Felting rate estimators	Merino 64^s	Border Leicester	Ryeland	South-down
Raw wool	D_f (g/cm^3)	0.194 (100)	0.177 (91)	0.112 (58)	0.081 (42)
	F (%)	86.8 (100)	83.3 (96)	77.2 (89)	68.9 (79)
Slubbing	D_f (g/cc)	0.179 (100)	0.161 (90)	0.106(59)	0.057 (32)
	F (%)	84.3 (100)	82.0 (97)	74.4 (88)	48.7 (58)
Yarn	Linear shrinkage(%)	37.1(100)	21.5(58)	28.9 (78)	20.4 (55)
	S.E. of mean	±1.2	±1.1	±0.9	±0.5
Fabric	Area shrinkage (%)	31.4(100)	22.3(71)	19.3(61)	14.9(47)
	S.E. of mean	±2.0	±1.0	±1.6	±1.9
Shrink-resisted fabric	Area shrinkage (%)	33.2(100)	21.2(64)	19.3(58)	13.5(41)
	S.E. of mean	±0.8	±0.1	±1.6	±1.8

The number inside the bracket indicates an index based on the merino wool felting rate as 100 units.

TABLE 4.—VARIATION OF THE SPECIFIC RESISTANCE TO COMPRESSION (g/cm^2) (at 10 cm^3/g Bulk Compression) WITH WOOL TYPES.

Sample	Merino 64^s	South-down	Ryeland	Border Leicester
Raw wool	129	229	202	113
Slubbing	80	167	142	62
Shrink-resisted elubbing	162	271	239	95

established negative correlation between the felting rate of random wool assemblies and their specific compressional load. In addition, a critical comparison of the loose wool with yarn felting behaviour (Table 3) clearly shows an interaction between the breeds as observed elsewhere[2–4,5,27] whereas the change of bulk compressibility with processing up to the yarn stage did not exhibit any interaction between the breed and among these 4 wools.[27]

However, the distribution of loose wool felting rates closely follows the index of the fabric felting rates although the relation between them (Fig. 3) is definitely curvilinear and the parameter F rather than D_f appears to give a better fit. It may also be pointed out that D_f possesses a physical dimension of ML^{-3} in terms of mass (M) and length (L), whereas F is dimensionless as the usual estimators of both yarn and fabric felting rates. Nevertheless, both F and D_f show an almost similar trend in their relations with fabric felting rate which, however, follows the same order of rating in both the treated and untreated wools. But the outcomes of the same shrink-proof treatment manifest considerable variability (Table 3) which is probably due to the difference of available fibre surface (a function of diameter) in a given mass and/or the natural variations in vulnerability of scale-coating.[4] The latter may produce differential change of the directional frictional effect[5,6,27,32,33] (causal basis of wool felting) with progressive washing of the treated wools.

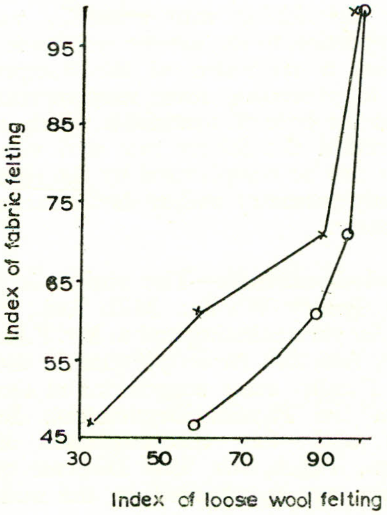

Fig. 3.—Relation between fabric fetling and slubbing felting rates of 4 wool types; percentage of bulk density change F (O), felt ball density (D_f) (X).

In addition, the most outstanding observation of this analysis is the very high felting rate of the shrink-proofed fabrics which were, however, knitted from the treated yarns. And the treatment had increased the specific resistance to bulk compression of the slubbings (Table 4) in various proportions which appear to be positively correlated with the rise of felting rates that is attributable to the treatment. For example, the increase of the compressional load produced a corresponding amount of slackening of the knitting stitch which, in turn, enhanced the felting propensity since the loosening of weave structure certainly increases the felting rate.[34] Conversely, a reduction of the specific compressional load due to processing stress is likely to increase fibre cohesion in the ordered assemblies. The cohesion tends to retard fibre mobility and the consequent felting rate as might have occured in the slubbings where the fibres were largely parallelised by carding.

Conclusions

A correlation between loose wool felting rate and the variation of liquor volume is beset with a significant between-breed interaction which is probably attributable to a limiting situation when the magnitude of the applied compressive force tends to be equal to the antiscale frictional force of a particular wool assembly. In addition, the loose wool felting rate appears to be closely represented by the percentage of bulk density change rather than the actual density of the felted assembly. Eventually, an observed interaction in the variation of felting rate with progressive processing of various wools, suggests two opposing functions of bulk compressibility. Whilst in the random assemblies the felting rate generally varies in inverse proportion to the specific resistance to bulk compression, a reduction of the compressional load due to processing stress may increase fibre cohesion in the ordered assemblies which, in turn, tends to retard the felting rate and vice versa. This effect can be complicated by the restraint of the assembly geometry and/or its interaction with fibre geometry.

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