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BULL SAMPLING PROGRAMMES IN THE ARTIFICIAL BREEDING OF DAIRY CATTLE

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SUMMARY

An artificial breeding organization can maintain a steady supply of proven bulls for itself through the use of a bull-sampling programme. This involves choosing young, untried bulls on the basis of pedigree records and using them in the artificial breeding service to sufficient extent to provide enough daughters for reliable progeny tests, on the basis of which the better bulls are selected as replacements for the proven-bull team and the remainder discarded. When the proven-bull team is maintained in this manner, the likely genetic superiority for production of all cows sired through artificial breeding, can be predicted. The methods of doing this are outlined in this paper, with particular reference to New Zealand conditions. The choice of an optimum programme from a variety of possible programmes, involving variations in the factors affecting the daughter superiority of any particular one, is discussed. It is concluded that the two most important ways of increasing the superiority are to obtain the greatest number of inseminations possible from each proven bull, and to have all daughters of the unproven bulls in herds that are tested.

THE SUCCESS of artificial breeding in increasing dairy production depends on the widespread use of bulls that have proven themselves to be of above-average merit in this respect. In the initial stages of an artificial breeding (A.B.) organization, reliance is placed solely on the use of bulls proven under conditions of natural mating, but as the organization expands, sufficient of these may not be readily available. However, sires proven under conditions of artificial breeding soon become available. This is advantageous, because a bull's usefulness in A.B. depends on the production level of his daughters in a wide variety of herds, and a progeny test made under these conditions is a better guide to the bull's merit than is one made in a single herd, which is the usual situation with natural mating. Bulls selected for A.B. on the basis of natural proofs (those based on daughters born of natural service) will be at least 9 years old when re-appraised on the results of their A.B. proofs (those based on daughters born from artificial breeding). Their subsequent use in A.B. is therefore limited, and the extensive use of bulls proven in A.B. must consequently be based on purchasing young, unproven bulls and selecting the better ones from them on the basis of their A.B. progeny tests. Young bulls purchased for initial use at one year of age will then be only 5 years old when their progeny tests are available and selections made for the proven-bull team. Furthermore, if the young bulls are used just sufficiently to give enough daughters for a reliable progeny test, many more than will actually be required as proven bulls can be purchased, and only the very best retained for the proven-bull team when the progeny tests become available.

Proven bulls selected in this fashion can be used concurrently with naturally-proven sires, whose use in an A.B. scheme of static size will gradually diminish as increasingly more A.B.-proven sires become available through the bull-sampling programme. The diminishing need for naturally-proven sires means that a more selective choice of such bulls can be made when acquiring them, which is of particular use to an A.B. organization that is expanding, since its reliance on naturally-proven sires will be maintained for some time, until the programme is able to provide enough A.B.-proven sires of sufficiently high merit.

GROWTH OF ARTIFICIAL BREEDING IN NEW ZEALAND

Table 1 shows the growth of artificial breeding in New Zealand since 1953, when the New Zealand Dairy Board as it was then (now the New Zealand Dairy Production and Marketing Board) opened its first A.B. Centre at Newstead, near Hamilton. The general expansion has been nearly ten-fold in the seven years from 1953 to 1960; annual inseminations have increased from 78,000 to 667,000 and the expectation is that the three-quarter million mark will be reached this year (1962). The number of bulls used each year has increased in the same way, from 29 in 1953 to 296 in 1960.

The bulls used each year have been classified in Table 1 according to the nature of their proof at the time of use, either naturally-proven, A.B.-proven or unproven. Bulls with natural proofs have always been the major part of the proven-bull team, although the number with A.B. proofs has increased considerably, there being 2 in 1954, representing 8% of the proven-bull team, and 29 in 1960, representing 23% of the proven bulls in use that year. Some of these were naturally-proven when first used, but as records of A.B. daughters became available they were re-classed as A.B.-proven; for example, of the A.B.-proven

TABLE 1: GROWTH OF ARTIFICIAL BREEDING IN NEW ZEALAND

		Number of Bulls Used					
		Proven Bulls					
			Selected on A.B.				
Year	*Insemin-ations (nearest thousand)*	*Selec-ted on Natu-ral Proof*	*Pur-chased with Natural Proof*	*Pur-chased as Un-proven*	*Total*	*Un-proven Bulls*	*% of Insemin-ations by Unproven Bulls*
1953	78,000	12	0	0	12	17	23
1954	115,000	24	2	0	26	35	29
1955	225,000	36	0	2	38	42	20
1956	255,000	49	1	2	52	56	21
1957	327,000	51	2	5	58	63	23
1958	434,000	72	3	10	85	89	20
1959	575,000	93	6	12	111	128	18
1960	667,000	96	8	21	125	171	21

bulls used in 1960, eight were purchased with natural proofs and used on this basis in earlier years, and 21 of them had been selected on the basis of their A.B. proof alone.

The increased number of bulls selected on A.B. proof is a direct consequence of the expanding use of bull-sampling, accompanied by increases in the number of unproven bulls used each year, from 17 to 171 between 1953 and 1960. Although something over half the total bulls used in the stud each year have always been unproven, only some 20% of the total inseminations have been made with their semen, as shown in the last column of Table 1. There are two reasons for this lighter usage of the unproven bulls. First, the proven bulls have already established themselves by their daughter production and are therefore used as heavily as possible. Secondly, although the unproven bulls have been chosen with great care on the basis of their pedigree records, prediction of their daughter production level on this basis is not very reliable relative to prediction based on some actual daughter records, so that until these are available the unproven bulls are used only lightly. It is interesting to note at this stage how much more information about a bull's daughter level can be obtained from some of his own daughters than from records of other relatives. For example, it can be shown (see Appendix) that five daughters of a bull give a more reliable prediction of his true daughter level than does an infinite number of paternal half-sisters; even three daughters give as much information as 45 paternal half-sisters and two daughters are equivalent to 16 of them. Records of the bull's dam likewise contribute little, relative to records from daughters, two daughters giving more information than any number of records from the dam. This does not mean that half-sister and dam records are of no use; they are, and are given careful scrutiny in choosing the unproven bulls for use in A.B., from among the sons of the better sires (preferably those used in A.B.). Further and more reliable information is subsequently gained about the unproven bulls in the form of progeny tests, and on this basis the best among them are selected for the proven-bull team.

This then, is the basis of a bull-sampling programme, as discussed by Henderson (1956), and described by Henderson and Dunbar (1952) as providing "unusual opportunities" for improving production in dairy cattle. Young bulls are chosen from pedigree records for use as unproven bulls in the A.B. stud and their initial use is sufficient to ensure enough tested daughters four years later to provide a reliable proof. Over this period they are kept in reserve, and not used for inseminations. Progeny tests are evaluated as soon as the daughter records are available, and on the basis of these the top animals are put into the proven-bull team. Sufficient are selected to maintain the team at its required strength, the superiority of the bulls selected being directly affected by the intensity of selection that is available when the selection is made.

FACTORS AFFECTING SELECTION SUPERIORITY

The bulls brought into A.B. as unproven are above average as a result of their being chosen on their pedigree records. Selections from these bulls for the proven-bull team, on the basis of progeny-test results, will be additionally superior. The additional superiority, of the daughters of the bulls selected for the proven-bull team, over the daughters of all the young bulls from which selection was made, can be estimated for any bull-sampling programme. Two main factors govern the magnitude of this daughter superiority, the selection intensity that can be practised among the young bulls when their proofs become available, and the number of daughter records in these proofs. These factors are, in turn, conditioned by several aspects of the operation of a bull-sampling programme, which, together with certain characteristics of the A.B. scheme, must now be specified.

If the size of the A.B. scheme is T inseminations per year, with a proportion, P, of them being made with semen from proven bulls, then PT is the number of inseminations with proven-bull semen and $(1-P)T$ is the number with unproven-bull semen. Thus if the numbers of proven and unproven bulls are represented by N_p and N_u respectively, with the average number of inseminations per proven and unproven bull likewise being I_p and I_u, then

$$N_p = PT/I_p \text{ and } N_u = (1-P)T/I_u.$$

The selection intensity available when selecting bulls for the proven-bull team depends both on the number needed in order to maintain the team at its desired strength, and on the number of young bulls still alive when their proofs are obtained. The case of a static A.B. scheme only will be considered, one where the number of inseminations is assumed steady at T per year, and the number of proven bulls required is accordingly N_p, as given above. If, as given in the N.Z. Dairy Board Annual Report (1961, p. 88), approximately 25% of the proven bulls are lost each year owing to death, disease, infertility, old age and other causes, then the number of replacements that have to be found annually is $\frac{1}{4}N_p$. These have to be selected from those which remain, of the N_u unproven bulls first used in service four years previously. Assuming 70% remain, the $\frac{1}{4}N_p$ replacements will thus be selected from $(0.7)N_u$, so the selection intensity, s, available is

$$s = \frac{\frac{1}{4}N_p}{(0.7)N_u} = \frac{5PI_u}{14(1-P)I_p} \qquad \text{.............. (1)}$$

(The wastage rate among unproven bulls over a 4-year period has been assumed as 30%, although the figure now reported is close to 20% (*loc. cit.*, p. 90). The former was considered correct at the time the calculations were made, and has therefore been retained. It leads to a slight under-estimation of the daughter superiority compared with that obtained by using the more recent figure.) It is interesting to note that, with other factors remaining constant, an increase in the coverage per proven bull, I_p, improves the selection intensity (*i.e.*, s decreases), whereas increases in the unproven bull coverage, I_u, lead to increased s-values.

The second factor governing the estimated daughter superiority of the bulls selected is the number of daughters in the proofs of the young bulls. This, in turn, is governed by the number of inseminations, the conception rate and calvings to A.B., the percentage of abortions, the sex ratio and heifer losses during rearing. After taking these things into account, it is found (*loc. cit.*, p. 83) that, for every 100 inseminations, 21 heifers are reared, 97% of which survive to two years of age (*loc. cit.*, p. 103). Of the 20 resulting 2-year-olds, approximately 25% are tested, so that for every 100 inseminations made by an A.B. bull there are five tested daughters providing records for the bull's progeny test. The number of daughter records available for the proof of a young bull, d, is therefore

$$d = (0.05)I_u \qquad \text{(2)}$$

The superiority of daughters of the bulls selected as replacements for the proven-bull team can now be estimated (see Appendix) in terms of additive genetic merit for butterfat production, as

$$(32.5)\, i_s \sqrt{\left(\frac{9d}{30d + 370}\right)}$$

where i_s is the selection differential, being the mean value of the upper fraction s of a normal distribution with zero mean and unit variance. This is the estimated superiority of the daughters of the bulls selected to enter the proven-bull team, which in a static situation is that of the proven-bull team. But a measure of the superiority of the whole A.B. scheme must take into account the fact that daughters by the proven bulls are only a fraction, P, of all A.B. daughters. Therefore the estimated mean superiority or all A.B. daughters will be the above expression multiplied by P. Hence the estimated mean additive genetic superiority of all daughters born from A.B.

$$= P(32.5)i_s \sqrt{\left(\frac{9d}{30d + 370}\right)} \qquad \text{(3)}$$

EXAMPLE

The A.B. scheme as operated in 1960 provides a good example of the use of these formulae. There were approximately 700,000 inseminations, with 80%, namely 560,000 by proven-bull semen and 140,000 by unproven-bull semen. The coverage by the two groups of bulls was approximately 4,000 inseminations per proven bull and 800 per unproven bull (*loc. cit.*, pp. 89 and 91), thus giving the number of proven bulls as 560,000/4,000 = 140, and the number of unproven bulls as 140,000/800 = 175, which correspond closely to the numbers actually used, 125 and 171, given in Table 1.

The selection intensity is derived from equation (1) as

$$s = \frac{5\,(80\%)\,(800)}{14\,(20\%)\,(4{,}000)} = 0.29$$

for which the corresponding selection differential is $i_s = 1.18$. The number of daughters in the proofs of the young bulls is obtained from expression (2) as

$$d = (0.05)\,800 = 40$$

and then the estimated mean additive genetic superiority of all A.B. daughters is calculated from (3) as

$$(0.80)\,(32.5)\,(1.18)\,\sqrt{\left(\frac{9\,(40)}{30\,(40)\ +\ 370}\right)} = 14.7\text{ lb fat.}$$

This is the estimated daughter superiority for a bull-sampling programme with these characteristics, operating in a static A.B. scheme. No exact comparison can be made with the present A.B. organization in New Zealand because it has been expanding constantly ever since its inception. Nevertheless, since bull-sampling programmes have been in use since 1951 their outcome should not differ greatly from this estimate, and indeed this is the case. The average rating in 1960 of bulls selected on A.B. proof is reported as +24 (*loc. cit.*, p. 89) while that of bulls initially chosen as unproven in 1956 is +7 (*loc. cit.*, p. 91), a difference of 17 lb fat. Since the proven bulls constituted approximately 80% of the service, the average superiority of all A.B. daughters is 80% (17) = 13.6, which is close to the estimated value of 14.7.

SIRE PROVING SCHEME

Probably the greatest difficulty encountered in proving bulls in artificial breeding is that not all daughters are tested, and hence only the fraction of them which are contribute to the progeny tests. Thus, as has been seen, the progeny tests of A.B. sires in New Zealand are based on the records of only 25% of the daughters, five out of 20 resulting from each 100 inseminations. Having all daughters tested and included in the progeny tests would lead to greater accuracy in predicting the merit of the unproven bulls and hence to making more accurate selections for the proven-bull team, with a corresponding increase in the estimated daughter superiority. For example, the figure of 14.7 lb fat given above, based on 40 daughters, would bcome 16.2 lb based on 160 daughters. The desirability of having a means of ensuring that all the heifers of the unproven bulls which are reared are also tested, is immediately obvious, and to this end the Sire Proving Scheme was initiated in 1961. This is a scheme whereby a large, but limited, number of farmers receive semen from unproven bulls only, guaranteeing to have their herds tested three years later, and so provide records on all daughters of unproven sires. As compensation for receiving only unproven-bull semen, the farmers pay no artificial breeding fees and receive a rebate for the testing of each heifer that is by an unproven bull, the total rebate usually being sufficient to pay the herd-testing fees. All others using artifiicial breeding, constituting the bulk of the service, receive only proven-bull semen, for which the charges are a little higher than before the advent of the Scheme, when all users received a mixture of proven-and unproven-bull semen. Thus the Sire Proving Scheme is essentially self-financing and, above all, it provides production records from all reared daughters of the unproven bulls.

The Scheme's real advantage is not that the progeny test of an unproven bull can be based on an enormously large number of daughters, but that a reasonable number can be obtained without having large numbers of inseminations. Whereas the aim prior to the Sire Proving Scheme was 1,000 inseminations from each unproven bull, in order to obtain 50 daughters in a proof, only 300 inseminations are now required. Consequently, without increasing the proportion of all inseminations that come from the unproven bulls, the number of such bulls can be increased, which provides a greater degree of selection in making replacements for the proven-bull team, and hence an increased daughter superiority. Difficulties arise, of course, if one envisages having too great a number of unproven bulls—difficulties of financing their purchase and of keeping them four years until proofs are obtained. These practical problems impose an upper limit on the number of unproven bulls that can be handled satisfactorily. It appears that this limit has now been more or less reached, so that, by initiating the Sire Proving Scheme, the reduced number of inseminations required to obtain satisfactory proofs enables a higher proportion of all inseminations to be by proven bulls. If this were to mean more proven bulls and more replacements each year, the selection intensity would be lowered and the resulting daughter superiority of the proven bulls decreased. But if the number of inseminations per proven bull can be increased, then fewer such bulls will be required and the selection intensity when making replacements can be more favourable.

Increasing the number of inseminations that can be made from each proven bull is undoubtedly the direction in which greatest production improvement can be achieved through the use of bull-sampling programmes. The short breeding season in

New Zealand, concentrated into the few weeks from mid-September until mid-November, rather limits the amount of semen that can be collected from each bull. Thus, investigation into increasing the number of inseminations per bull has been directed towards making greater use of the semen that is collected, through new diluents or through inseminating with smaller quantities than 1 ml of diluted semen. The result of this work to date, carried out by P. Shannon, at the A.B. Centre, Newstead, has been the widespread practice in 1961 of inseminating with ¾ ml, and the consideration of using ½ ml this year. If this results in ½ ml, becoming the regular dose rate, with a corresponding increase in the number of inseminations per proven bull, then the daughter superiority will rise markedly.

TABLE OF VALUES

The effect of these many factors on the estimated daughter superiority can be seen from a study of Table 2, which shows estimated superiorities for a variety of bull-sampling programmes designed for an A.B. scheme of 700,000 inseminations. The table is divided into three sections, the first two describing the bull-sampling programmes and the third giving their estimated daughter superiorities. The first section concerns the unproven bulls, the proportion of all inseminations which they provide (20%, 15%, 10% and 5%), the number required per bull, and the resulting number of daughters in the progeny tests. The second section deals with the proven bulls, the proportion of all inseminations which they contribute, and the number of such bulls required according to whether each provides 4,000, 6,000 or 8,000 inseminations. The third section of the table shows the estimated mean additive genetic superiority of all A.B. daughters over the daughters of the unproven bulls, in pounds of butterfat; the entries under the heading *25%* apply when only 25% of reared heifers are tested, and those under the heading *100%* apply when all are tested. The first row of the table corresponds very closely to the A.B. scheme as it was in 1960. The superiorities of 14 and 16 under the heading *4,000* are the values discussed above. The remaining entries, 18, 19, 20, and 22, indicate the effects of increasing the inseminations per proven bull. General trends evident from the table are that:

(1) Increasing the number of unproven bulls increases the mean daughter superiority. The increases shown are not spectacular, but they become appreciable if the number of unproven bulls is raised to an impractical figure of 700 or more.

(2) Reducing the proportion of all semen from unproven bulls decreases the daughter superiority when 25% of daughters are tested, because of relatively few daughters in the progeny tests. But when all daughters are tested, decreasing the proportion to as low as 10% increases the daughter superiority, because sufficient daughters are still being obtained for reliable progeny tests.

(3) Increasing the inseminations per proven bull increases the daughter superiority in all situations.

OPTIMUM PROCEDURES

The real value of Table 2 is its use in finding bull-sampling programmes that give maximum daughter superiority within the confines of practical possibility. To facilitate discussion, possible alternatives or changes to the 1960 programme are identified by bracketed numbers alongside some of the daughter superiority values. The first of these, immediately below the initial row of the table and labelled (1), corresponds to increasing the unproven bulls to 200 (compared with 175 in the 1960 programme) and results in changing the superiority from 14 to 16 lb of fat. Increasing the number of unproven bulls still further, to 300 or 400, say (programmes 2 and 3), brings continued increases in the daughter superiority, from 16 to 17, and to 18 lb of fat, but practical problems associated with so many unproven bulls are then magnified. Equal and greater daughter superiorities can, however, be achieved through increasing the inseminations per proven bull, as discussed. For example, when they are increased from 4,000 to 6,000 the daughter superiority changes from 16 to 18 (programme 4) and a further increase to 8,000 inseminations per proven bull lifts it to 20 lb fat (5). This emphasizes the advantages to be gained from increasing the number of inseminations per proven bull; doubling them, and changing from (1) to (5), increases the daughter superiority by 25%, from 16 to 20 lb fat. Further, the number of proven bulls is decreased from 140 to 70—also a worthwhile consideration.

The effects of having all daughters tested rather than 25% of them can be demonstrated also. For example, if the 1960 operation (with a superiority of 14 lb fat) were changed from 175 to 200 unproven bulls (programme 1), and then changed to having all daughters tested, with a consequent decrease in the usage of unproven bull semen from 20% to 10%, then the daughter superiority rises to 18 lb fat (programme 6). This is both worth

TABLE 2: BULL-SAMPLING PROGRAMMES

	Unproven Bulls				*Proven Bulls*				*Average Superiority of A.B. Daughters*					
						No. of Bulls for an A.B. Scheme of 700,000 Inseminations			*Estimated Mean Additive Genetic Superiority of all A.B. Daughters over the Daughters of the Unproven Bulls used in A.B. (lb fat)*					
						Inseminations per Bull			*Inseminations per Proven Bull*					
									4,000		6,000		8,000	
									Percentage of Daughters from Unproven Bulls which are Tested					
Number	*Proportion of all Insems.* (%)	*Insems. per Bull for an A.B. Scheme of 700,000 Insems.*	*No. of Tested Dtrs. per Bull* 25% *tested*	*No. of Tested Dtrs. per Bull* 100% *tested*	*Proportion of all Insems.* (%)	*4,000*	*6,000*	*8,000*	*25%*	*100%*	*25%*	*100%*	*25%*	*100%*
175	20	800	40	160	80	140	94	70	14	16	18	19	20	22
200	20	700	35	140	80	140	94	70	16(1)	17	18(4)	20	20(5)	23
	15	525	26	105	85	150	100	75	15	18	18	21	20	23
	10	350	17	70	90	158	105	79	15	18(6)	17	21(7)	19	24(8)
	5	175	8	35	95	167	111	84	12	17	15	20	16	23
300	20	467	23	93	80	140	94	70	17(2)	20	20	23	21	25
	15	350	17	70	85	150	100	75	17	20	19	23	21	25
	10	234	11	46	90	158	105	79	16	21	18	24	20	26
	5	117	5	23	95	167	111	84	13	19	15	22	16	24
400	20	350	17	70	80	140	94	70	18(3)	21	20	24	22	26
	15	263	13	52	85	150	100	75	18	22	19	24	21	26
	10	175	8	35	90	158	105	79	16	22	18	25	19	26
	5	88	4	17	95	167	111	84	13	20	15	23	16	25

while and feasible, and is closely akin to the Sire Proving Scheme inaugurated last year—200 unproven bulls with 350 inseminations each, 70 daughters in their proofs, 158 proven bulls with 4,000 inseminations each, and an average superiority of all A.B. daughters of 18 lb butterfat. Furthermore, additional increases in the daughter superiority can be brought about by increasing the inseminations per proven bull, for example, increasing them from 4,000 to 6,000 leads to a superiority of 21 lb fat (programme 7) and if this could be doubled, by universally adopting the ½ ml dose, the daughter superiority would rise to 24 lb butterfat (programme 8). This is 70% greater than the current estimate of 14 lb and is certainly worth attaining.

CONCLUSIONS

It is concluded that the following procedures will lead to greatest production improvement being achieved through the use of bull-sampling programmes:

(1) Increase, to the greatest degree possible, the number of inseminations per proven bull.
(2) Purchase each year as many unproven bulls as possible, limited only by practical considerations, inclusive of making sufficient inseminations to have 50 to 60 daughters in the progeny tests.
(3) Utilize the proven bulls such that they contribute approximately 90% of the total semen output.

Inseminating with dose rates of less than 1 ml is in line with the first of these procedures and the Sire Proving Scheme incorporates the second and third.

APPENDIX

Parameters used for deriving the results referred to in the text are the heritability (in the "narrow sense"), the repeatability and the within-herd standard deviation of butterfat records. These have been denoted in the expressions below by h, r and σ respectively, and the estimates used in the calculations are those obtained from New Zealand data, namely $h = 0.30$ and $\sigma = 65$ (Searle, 1961a) and $r = 0.60$ (Castle and Searle, 1957). Heritability for this purpose is taken as that among groups of paternal half-sisters.

Relative Value of Pedigree Records

The correlation between a bull's true additive genetic merit and an estimate thereof is

$$\sqrt{\left(\frac{dh}{4 + (d-1)h}\right)}$$

when the estimate is derived from d daughter records, and is

$$\sqrt{\left(\frac{\frac{1}{4}Nh}{4+(N-1)h}\right)}$$

when the estimate is based on the records of N half-sisters. The two estimates contain equal information about the bull when these correlations are equal, in which case $N = 148d/(37-9d)$. Thus for $d = 1$, 2, 3 and 4 (number of daughters) the number of half-sister records, N, that contain equal information about the sire is 6, 16, 45 and 592, respectively. This method of setting up equivalence between two estimates is given in Searle (1961b) which includes a discussion of upper limits imposed by the form of the denominator. In this case d cannot exceed 5, indicating that 5 daughter records give more information than any number of half-sister records.

The correlation is

$$\sqrt{\left(\frac{\frac{1}{4}nh}{1+(n-1)r}\right)}$$

when the estimate of the sire is based on n records of his dam and where r is repeatability. Thus d daughter records, are equivalent to n records of the sire's dam, when $n=16d/(37-21d)$. Hence d cannot exceed 2, suggesting that 2 daughter records give greater information about the sire than do any number of his dam's records.

Daughter Superiority

The mean superiority of the daughters of the bulls selected, with selection intensity s, is $\frac{1}{2}Ri_s\sigma\sqrt{h}$ where R is the correlation between the true and estimated additive genetic merit of a sire, and i_s is the selection differential. Since the sire estimates are derived from progeny tests, R is the first of the three correlations given above, and consequently the expression for the mean daughter superiority reduces to

$$(32.5)\, i_s \sqrt{\left(\frac{9d}{30d+370}\right)}$$

as given in the text.

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