EXPERIMENTAL DESIGN IN AGRICULTURAL AND ANIMAL HUSBANDRY RESEARCH IN INDIA*

BY

DR. K. KISHEN

1. INTRODUCTION

I express my deep gratitude to my colleagues of the Indian Society of Agricultural Statistics for inviting me to deliver this address to such a distinguished gathering of eminent agricultural statisticians, scientists and research workers from all parts of the country. I take it that in conferring on me this honour, they have shown their appreciation of the vital role which experimental design, with which I have been associated for now more than four decades, plays in agricultural and animal husbandry research.

As is well-known, the basic principles of the theory of experimental design, involving the well-known concepts of replication, randomization and local control, were originated by R.A. Fisher between the year 1921 and 1925 at the Rothamsted Experimental Station with a view to providing the agricultural and biological research workers with a powerful statistical tool of experimental investigation. Soon after, in 1926, Fisher formulated the concept of factorial experimentation, which led him inevitably to introduce the concepts of total and partial confounding of high order interactions with inter-block differences in order to reduce the block size and thus improve the efficiency of the experiment.

The theory of confounding, including as it does the split-plot technique, was first systematically and comprehensively discussed by Yates in 1933. This concept was subsequently extended by him to agronomic tests involving a large number of varieties or treatments among which interactions do not exist or are of no particular interest, and he introduced the concept of balanced incomplete block (BIB) and lattice designs. Yates also developed the concept of recovery of inter-block information for enhancing the efficiency of these designs.

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A significant advance was made by Finney in 1945 when he introduced the concept of fractional replication of factorial arrangements which enables a factorial experiment, involving a large number of factors, to be carried out with only a fraction of the number of treatment combinations (or assemblies or runs) required for the complete factorial experiment.

Indian statisticians, under the leadership of R.C. Bose, have also made notable contributions to the theory of experimental design, and developed in 1940 the powerful tool of Galois fields and finite geometries which have been found to be extremely useful in the construction of confounded plans for symmetrical and asymmetrical factorial experiments, balanced incomplete block (BIB) and partially balanced incomplete block (PBIB) designs, fractional factorials, orthogonal arrays, balanced arrays, etc.

During the past decades, advanced research in the theory of experimental design is being pursued with vigour and a wide variety of asymmetrical, factorials, fractional factorials, search designs, response surface designs, mixture designs, PBIB designs, efficiency balanced (EB) designs, partially efficiency balanced (PEB) designs, supplemented block designs, etc., have been extensively investigated. However, emphasis during the past two decades has been largely on the development of a great variety of fractional factorial plans for both symmetrical and asymmetrical factorial experiments. These will be discussed in some details in Section 4.3 in view of their utility in agricultural and animal husbandry research.

The credit for the introduction of experimental design in agricultural research in India goes to the Indian (then Imperial) Council of Agricultural Research which was founded in 1929 on the recommendation of the Royal Commission on Agriculture. From its very inception, ICAR laid stress on the utilization of the new experimental techniques in agricultural research and created a Statistical Section at headquarters, which has, through the indefatigable labours of the illustrious statisticians who have been heading this Organization in succession during the past four decades, now developed into the Indian Agricultural Statistics Research Institute (IASRI).

The IASRI has exercised a powerful influence in the development of experimental design in agricultural research in the country during the past four decades and has been imparting training to agricultural research workers in the design and analysis of experiments with a view to enabling them to employ the most efficient designs in their experimental investigations. The institute has also played a very significant role, in collaboration with the other ICAR Institutes, Agricultural Universities, and State Departments of Agriculture, in the conduct of large-scale experimental programmes on agricultural crops, analysing their data and interpreting the results. This has enabled the Institute to formulate recommendations for the various regions of the country in regard to the optimum dosage of fertilizers and other inputs for different crops, which has contributed in no small measure to increased agricultural production. The Institute has also given a lead in the development of the theory of design of experiments and the contributions made by the school of workers on experimental design at the Institute have received international recognition.

I take this opportunity of recording my high appreciation of the significant role played by the Indian Society of Agricultural Statistics (ISAS) in the development of experimental design in agricultural research in the country by, *inter alia*, encouraging both theoretical and applied research in this area, holding regularly a session on reading of papers on design of experiments at its annual conferences and publishing valuable papers on the subject in its esteemed Journal (JISAS).

I also pay my tributes to my esteemed friend and colleague, Dr. Daroga Singh, the erstwhile Director of IASRI and Secretary of ISAS for more than a decade, and now on an FAO assignment as Senior Statistical Adviser to the Government of Jordan, for his lasting contributions to the development of agricultural statistics research in the country. He served both the above organisations with earnestness and dedication and contributed significantly to their development to their present stature. His life and work are a source of inspiration to all of us and we miss him very much today.

I shall now discuss briefly agricultural and animal experimentation in the country and also some recent developments in the theory of design of experiments which are likely to be of utility in agricultural and animal husbandry research.

2. Agricultural Experimentation

2.1. All-India Coordinated Agronomic Research Project (AICARP)

IASRI is collaborating with the other ICAR Institutes, Agricultural Universities and State Departments of Agriculture in carrying out large-scale experimental programmes, analysing their data and interpreting the results of analysis. An important function of the Institute is the design, analysis and interpretation of the results of experiments conducted under the AICARP. The two types of experiments carried out under this programme are : (*a*) Complex experiments at Model Agronomic Research Centres, and (*b*) Simple experiments on cultivators' fields. Under this project, about 600 Model Agronomic Experiments (MAE) and nearly 8000 experiments on cultivators' fields (ECF) are carried out annually. This project has been in operation since 1956-57 and has been modified from time to time to meet the needs of research in Crop Production. These experiments have been of great utility in formulating recommendations for maximizing production of various crops under different agro-climatic conditions. The designs used in MAE are randomized block designs (RBD), complete factorials in RBD, split plot designs, split-split-plot designs, confounded factorials etc. In ECF, which are mostly unreplicated randomized blocks of 10 to 12 plots each (sometimes a split-plot design is also adopted), the treatments tested are those selected suitably out of the totality of treatment combinations (or assemblies or runs) in the corresponding factorial design. In my view, great economy in resources will be brought out if, instead of using unconfounded or confounded complete factorial designs in MAE, optimal fractional factorial plans are adopted. In ECF, use of optimal fractional factorial plans would result in optimum utilization of experimental resources. I have discussed this in greater detail in Section 4.3.

I find that while analysing the fertilizer response data from MAE and ECF the usual practice is to fit an ordinary second degree polynomial which is necessarily symmetrical with respect to its modal value. However, in many situations, the response curve is skewed and a second degree polynomial is, consequently, likely to be a poor fit. I understand that V.K. Gupta and A.K. Nigam have examined this point and their results indicate that a model having a linear term and an inverse term is more appropriate in such cases (IASRI Report, 1981).

2.2. National Index of Agricultural Field Experiments (NIAFE)

An important project being operated by IASRI since 1955 is the All-India Scheme of National Index of Agricultural Field Experiments (NIAFE) with a veiw to collecting and systematically maintaining at a central place the experimental data of all the agricultural field experiments (excluding purely varietal trials) conducted in the country at research centres and on cultivators' fields by the State Departments of Agriculture, Agricultural Universities and ICAR Institutes, and under the All-India Coordiated Crop Improvement Projects and other Coordinated Research Projects of the ICAR. The results of the experiments carried out since 1947, alongwith the relevant ancillary information, are being published in the form of series of compendia volumes for successive periods. Three such series have so far been published. With the increase in the computer facilities at the Institute as a result of the installation of a Burroughs B-4700 Computer in February, 1977, the experimental data are now proposed to be stored in magnetic tapes in such a way that selective retrieval would be feasible.

From the data collected under the NIAFE Scheme, it appears that about 48% experiments are simple RBDs, nearly 19% are complete factorials in RBDs, about 27% are split-plot designs, and the remaining 6% are generally confounded factorial designs. As already remarked, adoption of appropriate optimal fractional factorials instead of unconfounded and confounded complete factorials would lead to considerable economy in experimental resources in view of the much smaller number of plots required for a fractional factorial. The split-plot design and its variants, namely, strip plot design, split-split plot design, split-plot-cum confounded design, etc., have been quite popular with agricultural experimenters. However, it would be preferable not to use them except when practical considerations necessitate their adoption. This is because the over-all efficiency of these designs is rather low, there being an increase in precision of sub-plot comparisons at the cost of main-plot comparisons. I am particularly opposed to their adoption at the Model Agronomic and other Research Centres in the country where experiments are undertaken under fairly controlled conditions which permit the adoption of more efficient confounded factorial or, preferably, optimal fractional factorial designs.

2.3. Statistical Evaluation of Experiments

I find that no statistical evaluation of the experiments, for which data have been collected under the NIAFE Scheme, has so far been undertaken. An appropriate technique for statistical evaluation of agricultural field experiments has recently been developed by Bajpai and Nigam [JISAS, Vol. 32 (2), 1980, pp. 41-51], which is an improvement over the earlier technique given by Seth *et al.* in 1958.

Nigam and Bajpai (IASRI Report, 1980) have employed this technique for statistical evaluation of 818 field experiments conducted on the Wheat crop in the U.P. State during 1966–71 and have suggested several corrective measures in regard to the selection of treatment levels, plot size and choice of the experimental site for disease control trials. This is a useful study, but no such work is available on any other crop or experimental programme. In my opinion, such statistical evaluation should form an integral part of all the experimental programmes sponsored by the ICAR and also of the Scheme of the NIAFE. Intensive research on statistical evaluation may also be undertaken at the IASRI as it may lead to further refinements in the technique developed by Bajpai and Nigam.

2.4. Optimum Amount of Experimentation

No study has so far been carried out on data from agricultural field experiments with a view to determining the optimum amount of experimentation for these experiments in the country, although a suitable statistical methodology for making such a study was developed by Yates in 1952. Such a study would be of considerable value in agricultural research as it would enable assessment of the present status of agricultural experimentation in the country and would also provide guidelines for efficient planning of agricultural field experiments in future. IASRI has already carried out such a project for working out the optimum amount of experimentation in animal nutrition (IASRI Report, 1980) and may like to undertake a similar project on agricultural field experiments.

2.5. Coefficient of Variation (C.V.)

The coefficient of variation (C.V.) of an experiment, which is the percentage standard deviation divided by the mean, is an important measure of the magnitude of the experimental error. It depends on a number of factors such as the size and shape of plots and blocks, the number of plots per block, their arrangement in the field, the homogeneity or otherwise of the experimental material etc. A high C.V. in an experiment is indicative of its low precision as a result of faulty formation of blocks, choice of inappropriate plot size, heterogeneity of the experimental material, etc.

Bhargava and Batra (Proceedings of the Fourth Conference of Agricultural Research Statisticians, 1979; pp. 174-175) worked out the C.Vs. for experiments for which data have been collected under the NIAFE scheme and found that about two-thirds of experiments on the Wheat, Paddy and Barley crops and over 60% experiments on the Maize and Ragi crops have C.V. up to 20%, whereas in about 20% experiments on these crops the C.V. falls in the range of 20% to 30%. For perennial and vegetable crops, the C.V. was found to be high in a large number of experiments, which was mainly ascribable to high variability in the experimental material.

Nigam and Bajpai (IASRI Report, 1980) found that in 282 out of the 818 experiments on the Wheat crop in U.P., or in about 34% experiments, the C.V. was more than 15%. In experiments on cultural treatments like sowing date, depth of ploughing, etc., the C.V. exceeded 15% in about 80% of the experiments.

It would thus be seen that a fairly large number of agricultural field experiments in the country have low precision owing to their faulty execution and other factors. This calls for appropriate corrective action in future experimentation.

2.6. Quality of Data

As stated in Section 2.2, agricultural field experiments are conducted at the Model Agronomic and other Research Centres in the country and a large number of experiments are carried out on cultivators' fields. As remarked by Bhargava and Batra, the experiments planned at research centres are generally carried out under fairly controlled conditions, ensuring proper selection of sites and uniformity in the conduct of agricultural operations and other practices to be adopted in an experiment. Besides, proper supervision is generally exercised by qualified research staff at the Centres, and thus the experimental data are of fairly good quality. However, more intensive over-all supervision by scientists of the IASRI would further improve the quality of the experimental data and will also have a salutary effect on the proper conduct of the experiments.

In the case of experiments on cultivators' fields, however, the situation is entirely different. Here the number of experiments carried out is very large, being about 8000 each year, and uniform sites cannot always be selected in cultivators' fields. Besides, the conduct of the experiments has to be entrusted to Field Assistants, who are much less qualified than the research staff and are also often careless in carrying out accurately the large number of experiments they are required to deal with. The experimental plot is also usually large and the field staff frequently commit border and other errors in the collection of data. Inevitably, therefore, the huge mass of data collected under these experiments is generally of considerably poorer quality than those from experiments at research centres. Effective supervision of field work by qualified statistical and other research staff alone can bring about the much-needed improvement in the quality of these data.

The question of improvement of the quality of experimental data has been under the active consideration of IASRI in recent years, and the matter was discussed in some detail at a symposium held at the Fifth Conference of Regional Supervisors and staff of NIAFE organized by the Institute at Kalyani (W.B.) in October, 1979. It was suggested that the statisticians should be associated with the planning of experiments so that they may help in eliminating the various sources of error which would affect the quality of data. However, as I have stressed in my concluding remarks, the statisticians should work in close collaboration with the experimenters at all the stages of an experimental investigation as that would go a long way in improving the quality of data.

It was also suggested at the symposium that the field work should be adequately supervised by the scientists responsible for the experimental programme and that all types of data collected by the scientists working in the Universities should be carefully scrutinized. Finally, it was recommended that a brochure on improvement of the quality of experimental data be prepared by IASRI for the benefit of the scientists engaged in the planning, conduct and analysis of experiments. I presume these recomendations are under implementation.

3. Animal Experimentation

3.1. National Index of Animal Experiments (NIAE)

A large number of animal experiments are carried out in the country in the disciplines of animal and poultry nutrition, dairy science, disease control, breeding and animal physiology etc., by Central and State Research Institutes and, in certain cases, by some private research organizations also. Since 1966, IASRI has undertaken a project called the National Index of Animal Experiments (NIAE) with a view to assembling together in one place the processed results of all experiments on animals and publishing them in the form of compendia volumes for the different research stations. Several of these volumes containing the results of animal and poultry nutrition experiments for various research stations have already been published and some others are ready for publication.

3.5. Some Further Suggestions

I would also suggest that each compendium volume of NIAE for a research station should contain a detailed note giving, *inter alia*, the distribution of experiments (excluding nutritive value experiments) according to the different designs adopted, the number of experiments where no standard design was used (excluding nutritive value experiments), statistical evaluation of the experiments conducted, an appraisal of the quality of experimental data and suggestions for improvement in the planning and execution of experiments and analysis and interpretation of the data. This note should also be communicated to the research station concerned for guidance and implementation of the suggestions for bringing about improvement in its experimental programme in future.

4. Some Recent Developments in Experimental Design

I shall now discuss briefly some recent advances in experimental design which are likely to be of use in agricultural and animal husbandry research. This will be considered under the heads: (*a*) Incomplete block design, (*b*) Asymmetrical factorial design, and (*c*) Fractional factorial designs.

4.1. Incomplete Block Design

Balanced incomplete block (BIB) and lattice designs were originated by Yates in 1936 to meet the needs of agricultural research workers when confronted with the problem of testing a large number of varieties or treatments among which interactions do not exist or are of no particular interest.

The most general incomplete block design is characterized by the parameters

$$v, b \,;\, r_1, r_2, .., r_v \,;\, k_1, k_2, ..., k_b \,;\, \lambda_{ij},$$

v being the number of varieties to be tested, b the number of blocks, $r_i (i=1, 2, .., v)$ the number of replications of i-th variety, $k_j\ (<v)\ (j=1, 2, ..., b)$ the number of plots in the j th block, and λ_{ij} the number of blocks containing the i-th and j-th varieties together. The problem of evolving practically useful classes of designs, which are particular cases of the above most general design, has been extensively investigated during the past four decades. The first fruits of this research are the partially balanced incomplete block (PBIB) designs introduced by Bose and Nair in 1939 and later generalized by Nair and Rao. Subsequently,

considerable work was done by Bose and his coworkers at North Carolina on the classification and analysis of PBIB design with two associate classes. In recent years, association schemes for PBIB designs involving three or more associate classes have been investigated mainly by Harshbarger, Nair, Roy, Vartak, Raghavarao, Singh and Shukla, Tharthare, Raghavarao and Chandrasekhararao, John, and Kishen and Shukla.

The BIB and PBIB designs have somewhat limited utility for varietal and other experiments because these usually involve a large number of replications. PBIB designs with only two replications were, therefore, studied by Nair in 1950 and 1951 and he gave many interesting examples of PBIB designs with 2, 3 or 4 associate classes, having two replications. In 1951, Bose exhaustively enumerated two-associate PBIB designs involving two replications.

Two-replicate PBIB designs with four or more associate classes have been recently investigated by Kishen and Shukla and they have developed the following three new series of the PBIB designs :

(*i*) *Rectangular Lattice Design* (*RLD*). The parameters of this design are $v=p(p-1), b, r, k, \lambda_i$ $(i=1, 2,...4)$, $n_1=2(p-2)$, $n_2=(p-2)(p-3)$, $n_3=2(p-2)$ and $n_4=1$; $p^i_{jk}(i, j, k=1, 2,...4)$, p being any positive integer, of which the simple rectangular lattice developed by Harshbarger in 1947 comes out as a special case.

Another two-replicate RLD has the parameters of the first kind given by

$$v=p(p-1),\ b=p,\ r=2,\ k=2\ (p-1),$$

$$\lambda_1=1,\ \lambda_2=0,\ \lambda_3=1,\ \lambda_4=2.$$

(*ii*) *Extended Rectangular Lattice Design* (*ERLD*). This is a PBIB design with ten associate classes, of which the parameters are : $v=p(p-2)$, b,r,k, λ_i $(i=1,2,...,10)$, $n_1=n_2=n_3=1$; $n_4=n_5=2$; $n_6=n_7=n_8=n_9=2\ (p-4)$; $n_{10}=(p-4)\ (p-6)$; $p^i_{jk}\ (i.j,k=1,2,\ ...,10)$, where p is an even positive integer $\geqslant 8$.

If $p=4$, the ERLD degenerates into a PBIB design with five associate classes ; and for $p=6$, we get a PBIB design with nine associate classes.

3.2 Design of Animal Experiments

On the basis of the data collected under this project, it has been reported by Bajpai, Nigam and Dey ("Optimum amount of experimentation in animal nutrition", IASRI Report, 1980) that in the case of 977 experiments on animal nutrition carried out at 19 research stations, for which statistical analysis was available, 408 (or 42%) are nutritive value experiments with only a single feed treatment, no comparison being made with a standard feed. No statistical design is required for conducting them. As for the remaining 569 experiments, in 87% of the experiments the design adopted was the completely randomized design (C.R.D.), in 9% experiments it was R.B.D., and in 4% experiments it was latin square design (L.S.D.). Out of these 569 experiments, about 50% experiments were of low precision and needed repetition.

As regards Research Centres individually, it appears from the compendia volumes of NIAE that the design mostly used is the C.R.D., the R.B.D. being generally adopted in only a small percentage of experiments. Other designs like L.S.D., switch-over and factorial designs are employed in only a very small percentage of experiments at only some of the Research Centres. The reasons advanced for the widespread use of the C.R.D. are that adequate number of animals of the same breed, same age, equal in number of lactations, of equal inter-calving interval, etc., are not available at the Research Stations and the experimenters find this design easy to adopt and analyse. Even the death of an animal, it is argued, does not adversely affect the experiment or require the use of the missing plot technique at the time of analysis of the data.

However, the animal experimenters must remember that the C.R.D. is a design of low precision and that optimum utilisation of their experimental resources can only be ensured by employing instead the recently developed designs like the optimal balanced fractional factorial designs, response surface designs, design for mixture experiments, incomplete block designs, etc., which may be most appropriate for their specific experimental problem. They must, therefore, closely collaborate with statisticians in the planning and execution of their experiments and in the analysis and interpretation of the experimental data. This would also bring about marked improvement in the quality of the data as the statisticians will also be able to give thought to the problem of eliminating the various errors that are likely to be committed in the collection of data. I understand that some of these points have been considered by

Bajpai, Nigam and Dey in their paper entitled "Power of Analysis of Variance Test in Animal Experimentation" [Abstract published in JISAS, Vol. 31 (3) 1979, p. 93].

3.3. Optimum Amount of Experimentation in Animal Nutrition

IASRI has carried out a project with a view to developing a statistical methodology for determining the optimum amount of experimentation in animal nutrition research, following the general principles laid down by Yates in 1952.

This is a useful study by Bajpai, Nigam and Dey (IASRI Report, 1980) and has been of help in assessing the present status of experimentation in animal nutrition and providing guide-lines for efficient planning of future experiments. On the basis of this study, it was found that 2100 experiments would be needed in future for obtaining optimum return out of livestock population and its feed resources in the country. In view of the low precision of the experiments on which this study is based, this estimate may be somewhat on the high side and less number of experiments may have to be conducted in future if efficient and appropriate recently developed designs, as indicated earlier, are adopted in animal experimentation. For bringing about the much-needed improvement in animal husbandry research in the country, it seems necessary to carry out on a regular basis an All-India Coordinated Research Project on Animal Experimentation, to be sponsored by the ICAR, analogous to the AICARP of the ICAR. In the first instance, however, it may be restricted to animal nutrition experiments at only research stations.

3.4. Statistical Evaluation of Animal Experiments

As I have already said earlier, statistical evaluation must constitute an integral part of all experimental programmes in agricultural research, and this seems all the more imperative in respect of animal experiments. However, the technique of statistical evaluation developed by Bajpai and Nigam for agricultural field experiments may need some modification for being rendered suitable for evaluating animal experiments. I am happy to learn that the work of statistical evaluation of animal nutrition experiments is already in progress at the IASRI and a project entitled "Overview of the designs adopted in animal nutrition experimentation in India with recommendations for use of new designs in appropriate situation" has been undertaken. I would, however, urge that the scope of this project should be speedily broadened to cover all animal experimentation in the country.

Four series of two-replicate ERLDs can be readily constructed, of which the parameters of the first kind are :

(a) $v=p(p-2)$, $b=2p$, $r=2$, $k=p-2$, $\lambda_1=\lambda_2=\lambda_3=\lambda_4=0$, $\lambda_5=\lambda_6=1$, $\lambda_7=\lambda_8=\lambda_9=\lambda_{10}=0$.

(b) $v=p(p-2)$, $b=p$, $r=2$, $k=2(p-2)$, $\lambda_1=0$, $\lambda_2=2$. $\lambda_3=0$, $\lambda_4=\lambda_5=\lambda_6=1$, $\lambda_7=0$, $\lambda_8=1$, $\lambda_9=\lambda_{10}=0$.

(c) $v=p(p-2)$, $b=p$, $r=2$, $k=2(p-2)$, $\lambda_1=2$, $\lambda_2=\lambda_3=0$, $\lambda_4=\lambda_5=\lambda_6=\lambda_7=1$, $\lambda_8=\lambda_9=\lambda_{10}=0$.

(d) $v=p(p-2)$, $b=p$, $r=2$, $k=2(p-2)$, $\lambda_1=\lambda_2=0$, $\lambda_3=2$, $\lambda_4=0$, $\lambda_5=2$, $\lambda_6=1$, $\lambda_7=\lambda_8=0$, $\lambda_9=1$, $\lambda_{10}=0$.

(*iii*) Truncated Triangular Design (TTD). This is a PBIB design with five associate classes, of which the parameters are :

$$v=(p-2)/2, \quad b,r, \quad k, \quad \lambda_i(i=1, \; 2,\ldots,5), \quad n_1=1, \quad n_2=2,$$
$$n_3=n_4=2(p-4), \; n_5=(p-4)\,(p-6)/2, \; p^i_{jk}(i,j,k=1,2,\ldots,5)$$

where p is any even positive integer$\geqslant 8$.

For $p=4$, the TTD degenerates into a PBIB design with two associate classes, and for $p=6$, into a four-associate class PBIB design.

Two series of two-replicate TTDs can be readily obtained, of which the parameters of the first kind are :

(a) $v=p(p-2)/2$, $b=p$, $r=2$, $k=p-2$, $\lambda_1=0$, $\lambda_2=\lambda_3=1, \lambda_4=\lambda_5=0$.

(b) $v=p(-2)/2$, $b=p/2$, $r=2$, $k=2(p-4)$, $\lambda_1=\lambda_2=2$, $\lambda_3=\lambda_4=1$, $\lambda_5=0$.

Two associate PBIB designs involving three replications were exhaustively enumerated by Roy and Laha in 1956.

It would thus be seen that a wide variety of PBIB designs, which are likely to be of utility in agricultural and animal husbandry research, are available in literature. Some of the PBIB designs have recently been found to be extremely useful for partial diallel crosses. Prem Narain and his coworkers at the IASRI have made valuable contributions in this area by developing efficient designs for partial diallel crosses and also some optimal plans.

The PBIB designs we have discussed so far have equal replications and equal block sizes. In some experimental situations, however, this may be a serious practical limitation. A very general class of incomplete block designs, called the partially efficiency balanced

(PEB) designs, has been recently developed by Puri and Nigam, of which the BIB and PBIB designs, as also cyclic designs, come out as special cases. PEB designs having varying replications and unequal block sizes can also be constructed. The class of variance-balanced block designs having unequal block sizes, varying replications and unequal λ.s recently introducted by B.N. Tyagi (JSPI, Vol, 3, 1979. pp. 333-336) is also a PEB design. In fact, it has been recently established by Satyabrata Pal (Calcutta Stat. Assoc. Bull., Vol. 29, 1980, pp. 185-190) that PEB designs constitute the most general class of incomplete block designs which includes any conceivable design in the class of connected block designs.

Many of these designs can be easily analysed by using the characteristic roots and characteristic vectors of some matrix M_o. As shown by Puri and Nigam, the anaysis of PBIB and related designs is much easier if these are analysed as PEB designs.

Mention may also be made of new class of augmented or supplemented block designs recently developed by Puri, Nigam and Narain, which are obtained by adding supplementary treatments to PBIB and PEB designs, which are again PEB designs and can be easily analysed. These designs are likely to be particularly appropriate in plant breeding trials and other similar experimental situations in which adequate material may not bc available on new strains in contrast with the standard varieties where there is no such limitation.

4.2. Asymetrical Factorial Designs

Asymmetrical factorial designs have been extensively investigated in recent years by Nair and Rao, Kishen and Srivastava, Das, Kishen and Tyagi, Kishen and Shukla, Aggarwal and Singh and others and a number of balanced asymmetrical factorial (BAF) and partially balanced assymmetrical factorial (PBAF) designs of practical utility have become available for adoption in agricultural and animal husbandry research.

Mention may be made here of several classes of two-replicate BAF and PBAF designs developed by Kishen and Shukla by suitably identifying the varieties of a two-replicate PBIB designs with the treatment combinations of the associated asymmetrical factorial design. The analysis of these designs can be done in an elegant manner with the help of the characteristic roots and vectors of NN′, where N is the incidence matrix of the PBIB design.

Let us first consider a triangular PBIB design for which $v=p(p-1)/2$. Asymmetrical factorial designs involving two factors A and B may be obtained from this design by suitably identifying the varieties of the design with the treatment combinations of the asymmetrical factorial design. Two cases arise according as p is even or odd, *i.e.*, for $p=2s$ and $p=2s+1$, s being any positive integer. From a two replicate triangular PBIB design, of which the parameters of the first kind are :

$$v=p(p-1)/2,\ b=p,\ k=p-1, r=2, \lambda_1=1,\ \lambda_2=0, n_1=2(p-2),$$
$$n_2=(p-2)(p-3)/2,$$

we shall, therefore, obtain the two series of two-replicate asymmetrical factorial designs of the types $(2s-1)\times s$ and $(2s+1)\times s$, of which the first is a PBAF design and the second a BAF design.

Similarly, by using an RLD for which $v=p(p-1)$, we obtain, taking $p=2s$ and $p=2s+1$, the two series of the two-replicate asymmetrical factorial designs of the types $(2s-1)\times s\times 2$ and $(2s+1)\times s\times 2$ involving three factors, of which the first is a PBAF design and the second a BAF design. Consequently, with each of the two RLDs involving two replications are associated with the aforesaid two series of asymmetrical factorial designs, each having two replications.

In the case of an ERLD, $v=p(p-2)$, where p is an even positive integer $\geqslant 8$. taking $p=4u$ and $p=4u+2$, where u is any positive integer $\geqslant 2$, we obtain corresponding to a two-replicate ERLD, the two series of two-replicate asymmetrical factorial designs of the types $(2u-1)\times u\times 2^3$ and $(2u+1)\times u\times 2,^3$ involviug five factors, of which the first is a PBAF design and the second a BAF design. As there exist four types of two-replicate ERLDs, from each of them we obtain the above two series of asymmetrical factorial designs, each in two replications.

Finally, we take a two-replicate TTD for which $v=p(p-2)/2$, p being any even positive integer $\geqslant 8$. Taking, as before, $p=4u$ and $p=4u+2$, where u is any positive integer $\geqslant 2$, the two series of associated two-replicate asymmetrical factorial designs come out to be $(2u-1)\times u\times 2^2$ and $(2u+1)\times u\times 2^2$, which involve four factors. Of these, the first is a PBAF design and the second a BAF design. As there are two types of two-replicate TTDs, from each of these we shall obtain the aforesaid two series of asymmetrical factorial designs, each in two replications.

Kishen and Shukla have also developed three general series of $q \times 2^2$ PBAF designs of the m-th order obtained from the associated pairwise partially balanced (PPB) designs, which provide some practically useful designs in two replications for $q=4$, 6, 8, etc.

4.3. Fractional Factorial Designs.

In factorial designs involving a large number of factors, the number of treatment combinations (or assemblies or runs) in the complete factorial scheme becomes unduly large, and adoption of even a single replication is beyond the resources of the experimenter. In such situations, it is imperative to resort to fractional replication in which only a fraction of the total number of treatment combinations required for a complete replication have to be tested. In agricultural and animal husbandry research, therefore, fractional factorials are likely to be of considerable practical utility as these would result in great economy in experimental resources owing to their small size as compared to complete factorials.

Fractionally replicated designs were originated by Finney in 1945 and have been the object of extensive research in recent years. As a result, a wide variety of fractional plans have become available for both symmetrical and asymmetrical factorial experiments. Fractional replicates of the type $\frac{1}{s^k}$ (s^m) $(k<m)$ for symmetrical factorials are called standard (or regular) fractional factorials and others, irregular factorials.

The term "Resolution" of a fractional plan was introduced by Box and Hunter in 1961 for purposes of classifying the fractional factorial designs. A fractional factorial is said to be of Resolution R if no p-factor effect is aliased with any other effect containing less than $R-p$ factors, so that the smallest interaction in the defining contrast (or alias subgroup) is an R-factor interaction. Thus, a Resolution III plan is one in which a main effect is aliased with two factor and higher order interactions. Similarly, a fractional factorial is said to be of Resolution V if a main effect is aliased with four factor and higher order interactions and a two-factor interaction is aliased with three-factor and higher order interactions. Thus. a Resolution III plan permits the estimation of the mean and all main effects, assuming two-factor and higher order interactions to be negligible. These are, therefore, also called main-effect plans. In Resolution V plans, however, the mean,all main-effects and two-factor interactions are estimable; assuming three-factor and higher order interactions to be negligible. These, therefore, are, particularyl appropriate in agricultural and animal husbandry research.

Fractional factorials which permit the estimation of all estimable effects orthogonally, i.e., in which the estimates are uncorrelated, are called orthogonal fractional plans. However, if the estimates are correlated, the plan is termed non-orthogonal. It may be mentioned that standard fractional factorial are orthogonal plans. It is also possible to obtain orthogonal fractional plans which are not standard fractions.

A concept of fundamental importance in the construction of fractional factorial plans is that introduced by C.R. Rao in 1947 in his orthogonal arrays of strength t. An $N \times m$ array with s symbols is said to be an orthogonal array of strength t if every $N \times t$ submatrix of the array contains each of the s^t ordered t-plets of the s symbols exactly μ times. Obviously, $N = \mu s^t$. The orthogonal array may be denoted by (N, m, s, t). If we identify the m columns with the m factors and the s symbols of the i-th column with the s levels of the i-th factor, the N runs give an orthogonal fractional plan for s^m factorial, which is of Resolution $(t+1)$. When $t=2$, we obtain an orthogonal Resolution III (or main-effect) plan. If $t=4$, we shall get an orthogonal Resolution V plan. In general, an orthogonal array $(N, m, s, t+l<t)$ yields an orthogonal fractional plan for s^m factorial in N runs, in which all effects up to l factors are estimable when interactions of t or more factors are assumed to be negligible.

In orthogonal main-effect plans obtained from orthogonal arrays of strength 2, each level of one factor occurs equally frequently with each level of any other factor. However, the equal frequency condition is merely sufficient to guarantee orthogonal estimation and is not necessary. As shown by Plackett in 1946 and independently by Addelman and Kempthorne in 1961, a necessary and sufficient condition for the main effects of two factors to be orthogonal is that the levels of one factor occur with each of the levels of the other factor with proportional frequencies. The condition of proportional frequencies can be generalized to yield plans giving orthogonal estimates of main effects as also two-factor interactions, and so on. By use of this condition and the technique of 'collapsing of levels of factors, several types of orthogonal plans for asymmetrical factorials have been derived from orthogonal plans for symmetrical factorials.

The concept of orthogonal array was generalized to balanced arrays (B-arrays) by Chakravarti in 1956, who called them "partially balanced arrays". A B-array of strength t, denoted by (N, m, s, t), yields a non-orthogonal Resolution $(t+1)$ plan for s^m factorial in N runs.

Orthogonal fractional plans provide optimum estimates of various effects, which are mutually uncorrelated. However, these are uneconomic as they require much more than the desirable number of runs. It, therefore, becomes necessary to consider non-orthogonal or irregular fractions which involve less number of runs. Although any number of non-orthogonal plans can be obtained. only those plans can be of utility to the experimenter which provide highly efficient estimates of the effects. The problem of obtaining the best non-orthogonal design is connected with the property of optimality. The three most useful optimality criteria, popularly known as A, D and E-optimality, refer to the minimization of the trace, determinant and the largest root respectively of the variance-covariance matrix of the estimates of effects of a design. Among the class of available non-orthogonal fractional designs, an optimal design satisying one or more of the aforesaid criteria has, therefore, to be chosen.

During the past two decades, optimal designs have been extensively investigated. Trace-optimal balanced Resolution V designs for 2^m factorials $(t \leqslant m \leqslant 10)$ have been presented by Srivastava and Chopra in a series of papers, and trace optimal Resolution $(2l+1)$ factorial designs of the 2^m series have been obtained by Yamamota, Shirakura and Kuwada. Balanced fractional 3^m factorial plans of Resolution V have also been developed by Srivastava, Chopra and Kuwada.

I have already remarked in Sections 2.1 and 2.2 that use of optimal fractional factorial plans instead of unconfounded and confounded complete factorials at research centres in the country would result in great economy in experimental resources. I would specifically suggest the adoption in future of optimal balanced fractional factorial plans of Resolution V, in which main-effects and two-factor interactions are estimable, assuming the three factor and higher order interactions to be negligible.

In the case of ECF also, which are non-orthogonal fractions, containing ten to twelve treatment combinations, it has been shown by Singh and Nigam ("A class of optimal designs for cultivators' field trials', JISAS, 1978, Vol. 30 (1), pp. 94-100) that an appropriately chosen optimal fractional plan would be much more efficient and economical than that actually used by the ICAR. The designs for ECF at present in use may, therefore, be replaced by optimal fractional factorial plans. Research in optimal fractional factorial designs should be intensified at the IASRI with a view to developing optimal fractional factorial plans which would be the most appropriate in the various experimental situations that may arise in agricultural and animal husbandry research.

I may also refer here to the concept of search designs introduced by J.N. Srivastava in 1975 which is a significant contribution to theory of fractional factorials. In fractional factorials, it is assumed that all the higher order interactions are negligible. However, it has been the experience in agricultural and animal experiments that this is not always true; and that sometimes, whilst most of the higher order interactions may be negligible, a few of them may be non-negligible. Search designs allow searching of the non-negligible higher order interactions and their estimation, besides providing estimates of the mean main-effects, etc., as in the corresponding fractional factorial plan. Thus, unless one is absolutely certain that all the higher order interactions are negligible, search designs would necessarily be an improvement over the fractional factorial plans.

The theory of search designs opens up a fascinating and fruitful area of research in which intensive work needs to be done for developing designs which would be of utility in agricultural and animal experimentation.

5. Concluding Remarks

From the foregoing review of agricultural and animal experimentation in India and some recent developments in experimental designs which I have presesented to you this morning, it would be seen there is considerable room for improvement in the design and analysis of these experiments in view of the very significant advances made in recent years in the thory of design of experiments. The need for adopting the recently developed designs is particulary urgent in animal experimentation as animal experiments are usually inclined to adopt primitive designs of such low efficiency as the C.R.D., which results in avoidable waste of valuable experimental resources. As I have already stressed earlier, optimum utilization of these resources can only be ensured if the experimenters work in close collaboration with the statisticians at all the stages of an experimental investigation, namely, in its planning, in its execution and, finally, in the analysis and interpretion of its data. It is only then that the most appropriate designs fitting into the strategy of the experimental programmes undertaken in the country will be evolved, the many errors in the conduct of the experiments will be controlled and maximum information from the experimental data will be extracted to provide guidelines for future.

In conclusion, I would say that, in the final analysis, the success of all our experimental programmes and statistical endeavours will be judged by how far these have brought about increase in agricultural and livestock production in the country and have thereby contributed in some measure to raising the socio-economic conditions and living standards of hundreds of million of our countrymen, the majority of whom are cultivators who incessantly toil in the fields in order that we live. This laudable objective can only be achieved through the united efforts of the agricultural and animal husbandry research workers and the statisticians. I, therefore, make a fervent plea for a close, healthy, fruitful and harmonious collaboration between the experimenters and the statisticians in this task.