Factors Contributing to and Affecting the Cellulose Digestibility of Pelleted Roughage

John Russell Jahn

Follow this and additional works at: https://openprairie.sdstate.edu/etd

Recommended Citation
Jahn, John Russell, "Factors Contributing to and Affecting the Cellulose Digestibility of Pelleted Roughage" (1960). Electronic Theses and Dissertations. 2737.
https://openprairie.sdstate.edu/etd/2737
FACTORS CONTRIBUTING TO AND AFFECTING
THE CELLULOSE DIGESTIBILITY
OF PELLETED ROUGHAGE

BY

JOHN RUSSELL JAHN

A thesis submitted
in partial fulfillment of the requirements for the
degree Master of Science, Department of Animal
Husbandry, South Dakota State
College of Agriculture
and Mechanic Arts

June, 1960
This thesis is approved as a creditable, independent investigation by a candidate for the degree, Master of Science, and acceptable as meeting the thesis requirements for this degree; but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser

Head of the Major Department
ACKNOWLEDGMENTS

The author wishes to express his sincere appreciation to Dr. L. D. Kamstra, Associate Professor in Animal Husbandry, for his supervision and helpful suggestions during the preparation of this manuscript.

Acknowledgment is also made to Professor Richard D. Anderson, Head of Engineering Shops, for his assistance and suggestions during the perfecting of the model pellet machine.

Appreciation is also expressed to Delores F. Jahn, wife of the author, whose assistance and understanding made this work possible.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>REVIEW OF LITERATURE</td>
<td>4</td>
</tr>
<tr>
<td>Digestion Trials Using Pellets</td>
<td>4</td>
</tr>
<tr>
<td>Mechanical Factors of Pelleting</td>
<td>12</td>
</tr>
<tr>
<td>Digestibility and Structure of Roughage Components</td>
<td>16</td>
</tr>
<tr>
<td>METHODS OF PROCEDURE</td>
<td>19</td>
</tr>
<tr>
<td>Pellet Composition and Formation</td>
<td>19</td>
</tr>
<tr>
<td>In Vitro Rumen Fermentation</td>
<td>25</td>
</tr>
<tr>
<td>Infra-red Spectrophotometer</td>
<td>28</td>
</tr>
<tr>
<td>&quot;Proximate&quot; and Lignin Analysis</td>
<td>29</td>
</tr>
<tr>
<td>X-ray Diffraction</td>
<td>29</td>
</tr>
<tr>
<td>Hydrolysis and Crystallization of Cellulose</td>
<td>30</td>
</tr>
<tr>
<td>RESULTS AND DISCUSSION</td>
<td>31</td>
</tr>
<tr>
<td>In Vitro Rumen Fermentation</td>
<td>31</td>
</tr>
<tr>
<td>Infra-red Spectrophotometer and X-ray Diffraction</td>
<td>33</td>
</tr>
<tr>
<td>Infra-red Spectrophotometer</td>
<td>36</td>
</tr>
<tr>
<td>X-ray Diffraction</td>
<td>41</td>
</tr>
<tr>
<td>&quot;Proximate&quot; and Lignin Analysis</td>
<td>41</td>
</tr>
<tr>
<td>Hydrolysis and Crystallization of Cellulose</td>
<td>42</td>
</tr>
<tr>
<td>SUMMARY AND CONCLUSIONS</td>
<td>43</td>
</tr>
<tr>
<td>LITERATURE CITED</td>
<td>45</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table                             Page
I. TEMPERATURE AND PRESSURE COMBINATIONS USED    23
II. COMPOSITION OF BASAL MEDIUM FOR THE IN VITRO RUMEN
    FERMENTATION                            26
III. THE AVERAGE PERCENTAGE OF IN VITRO DIGESTION OF ROUGHAGES  32
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Parts of Base Pellet Machine</td>
<td>20</td>
</tr>
<tr>
<td>2. Complete Pellet Machine</td>
<td>22</td>
</tr>
<tr>
<td>3. Roughage Before and After Pelleting</td>
<td>24</td>
</tr>
<tr>
<td>4. Apparatus Utilized for In Vitro Digestion</td>
<td>27</td>
</tr>
<tr>
<td>5. Graphic Comparison of the Digestibility of First Stage Unpelleted Alfalfa-Brome, Western Wheat, and Little Blue Stem Grass with Its Pelleted Counterpart</td>
<td>34</td>
</tr>
<tr>
<td>6. Graphic Comparison of the Digestibility of Third Stage Unpelleted Alfalfa-Brome, Western Wheat, and Little Blue Stem Grass with Its Pelleted Counterpart</td>
<td>35</td>
</tr>
<tr>
<td>7. Comparison of Pelleted (10,000 lbs. per sq. in.) and Unpelleted Third Stage Alfalfa-Brome in a Potassium Bromide Pellet</td>
<td>38</td>
</tr>
<tr>
<td>8. Comparison of Pelleted (10,000 lbs. per sq. in.) and Unpelleted Third Stage Alfalfa-Brome in a Mineral Oil Cell</td>
<td>39</td>
</tr>
</tbody>
</table>
INTRODUCTION

The transition to the pelleting of natural feeding materials has produced many problems. Various opinions have been expressed by the investigators regarding possible solutions to these problems. The proper mechanical formation of the pellet or wafer has been studied by several investigators. Several necessary factors have been determined. The temperature ranges that will produce the best possible product, from a feeding standpoint, have been tested against various pressures. The fineness of grinding or chopping have also been considered, as they relate to the digestibility and economy of the finished product. Moisture and adhesive agents have been considered in determining what level is optimum for pelleting or wafering.

In addition to the mechanical factors, the actual composition of the product being pelleted must be considered. Cellulose and lignin, the most undigestible portions of plants, produce a direct effect on any results connected with digestibility. Any structural change brought about in either component would have a decided effect on its nutritive value.

The investigators engaged in feeding trials are not in total agreement on the benefits of pelleting. The reasons for increased rate of gain cannot be satisfactorily explained. Increased consumption and faster digestion have been advanced as possible explanations. However, some workers suggest that increased gain is not due to feed intake alone. Another factor discovered by several authors is that the greatest advantage from pelleted roughage is derived from the poorer quality
natural products. This concept suggests a change in the physical and/or chemical relationship between the natural and pelleted product.

A complete analysis of the problems present too broad a field to be covered in a single investigation. It is the intention, therefore, of this study to explore some of the more basic aspects of the pelleting process. An attempt will be made, in this pilot study, to determine what changes take place in the material that would cause an improved feeding value to be derived from the pelleted product. These specific objectives, as they pertain to the pelleting problems, will be considered:

1. In vitro digestion trials, comparing the digestibility of high and low quality pelleted roughage to its unpelleted counterpart.

2. Comparing similar samples of roughage in the pelleted and unpelleted state by the use of an infra-red spectrophotometer to determine if a difference in basic structure exists.

3. "Proximate" and lignin analysis of the pelleted and unpelleted roughage to determine any changes in composition.

4. An examination of the crystalline structure by the use of x-ray diffraction to determine if any structural changes have resulted from the pelleting process.
5. An examination of the molecular linkage by a polymer process to determine if depolymerization occurs during the pelleting process.
REVIEW OF LITERATURE

The invasion of agriculture by mechanization has greatly altered the livestock industry. The handling of bulky grains and roughages by conventional methods is being replaced by a more dense, compact product. This transition is being accomplished by the pelleting of all types of animal feeds. Mixed rations, as well as all-roughage rations in pelleted form, are taking the place of the dusty, bulky, hard to manage natural products. The pelleting process has created new horizons in the feed industry, necessitating subsequent readjustment and re-evaluation of former feeding values. On comparison trials between pelleted material and the material in its natural state, the results obtained have varied from a negative value for the pellets to a great advantage over its un-pelleted counterpart. A review of the literature will develop the reasons for the growth of the pelleting process, its complication by mechanical factors and the effects of the process on the material being pelleted.

Digestion Trials Using Pellets

The early work done on pelleting dealt with improving the ease of handling, condensation of materials and insuring a uniform diet for the animals fed. In the early stages of pelleting, pellets were composed of concentrate mixtures and were used because of their ease of handling and convenience. As the process of pelleting expanded, it was noted by Eaton et al. (1952), that the pelleting of dehydrated alfalfa not only improved its handling qualities, but also stabilized and improved the carotene
content. At the same time, it was also noted that the calves fed these pellets had a greater feed intake with greater feed efficiency than those fed meal or loose hay. Warren et al. (1952) added hydrated pellets to a ration of timothy-grass hay and grain for milk cows at the rate of 1.5 pounds per 100 pounds body weight. It was found that the consumption of the timothy-grass hay decreased while the dry matter, TDN and NFE, increased as did the milk production.

Sheep have played an important role in the determination of the digestibility of pellets. Among the early workers to use sheep for this purpose was Neale. Neale (1953) conducted a digestion trial comparing two pelleted rations, differing in roughage content, against a loose hay and grain control. It was discovered that of the two pelleted rations the one containing 60 per cent roughage, 30 per cent grain sorghum, and 10 per cent molasses proved superior to either the 50 per cent roughage, 40 per cent grain sorghum, and 10 per cent molasses, or the control ration. The results showed a saving of 3.13 pounds alfalfa and .17 pounds concentrate per pound of gain for the high roughage ration over the control lot. The pellet-fed lambs also gained 47 per cent faster than the control lot. During the same year, using sheep for the trial, Jordan et al. (1954) and Bell et al. (1954) found that pelleting increased efficiency and improved rate of gain slightly. Jordan, however, was comparing a good quality ration of alfalfa and corn, which in later years proved to be least affected by the pelleting process.

Similar results were obtained using cattle for experimentation by Webb and Gmarik (1955). At the conclusion of a yearling steer feeding
trial, it was found that the **pellet-fed steers gained more with lower** feed consumption than the **meal-fed steers getting the same** ration. The **pellet-fed steer selling price was slightly higher and on the basis of performance**,** pelleted feed was worth $6.39 per ton more than meal, less the cost of pelleting.**

As the popularity of pelleting increased, more emphasis was placed on the pelleting of straight roughage as well as that of **complete rations** for ruminants. Webb et al. (1955) conducted a trial by feeding a mixture of timothy-alfalfa hay to steer calves in the following forms: baled, chopped, **pelleted, or silage.** At the conclusion of the trial, it was found that the calves fed the **pellets consumed 50 per cent more dry matter and had made 90 per cent greater gain** per ton of feed than the calves on the baled or chopped hay.

Further work was done during 1955 to determine the effect of different forms of roughage on dairy cattle. Gardner et al. (1955) compared the feed consumption of dairy calves fed **chopped, long, ground, or pelleted hay.** The results indicated that the **pellet-fed calves consumed more hay and less calf starter, while gaining more, than those fed the hay in either the chopped, long, or ground form.**

To compare the effect of feeding a low and high quality roughage in **pellet and meal form to ruminants,** Cate et al. (1955) conducted a feeding trial on lambs. Three rations were fed in a meal and a pelleted form. The **first ration consisted of alfalfa meal and ground yellow shelled corn. The second ration consisted of timothy meal, ground yellow shelled corn, soybean oil meal and molasses to be equal to ration one in**
TDN and crude protein. The third ration was composed of timothy meal and
ground yellow shelled corn. The results of the trial indicated that
pelleting increased average daily gains and feed consumption on the two
rations using timothy as roughage. The feed required per 100 pounds of
gain was lower for all rations fed as pellets and the greatest advantage
in pelleting was with the lowest quality ration. It will be seen that
this factor becomes more apparent and important in later years.

The increasing interest in pellets may be shown by an experiment
conducted in England by Wright and Dudley (1955), in which a comparison
of the effects of pellets versus mash was made with Khaki-Campbell ducks.
This trial compared productivity and maintenance of body weight through
the fourth laying season. It was found that the pellet-fed group main-
tained a superiority over the mash-fed group in average weight and in
egg production. It was also noted that feed consumption for the two
groups was about equal.

Ruminants and poultry were not, however, the only forms of live-
stock to be tested on pelleted forms of rations. Results published in
1956 from trials conducted previous to that time by Thomas et al. showed
that pellet-fed swine reached market weight 12 days earlier with a feed
cost of $1.42 less per 100 pounds gain than the meal-fed pigs.

Work was continued to test the effects of feeding pellets to
lamb by Long et al. (1955). Lamb feeding trials were conducted to deter-
mine the effects of grinding and pelleting on the digestibility of a
ration. Three rations were used consisting of: 1. long hay and whole
grain, 2. the same ration when ground, and 3. the same ration when ground
and pelleted. The results showed that grinding lowered the digestibility, but pelleting restored it to that of the natural material. It was also found that the digestion coefficient of organic matter, crude protein and crude fiber was higher in the pelleted feed. Elaborating on the earlier work, which compared the per cent of roughage in the ration versus an unpelleted ration of the same composition, Neale (1955) conducted a lamb feeding trial to compare the roughage content of various pelleted rations. The results of his work indicated that the highest efficiency was reached at a roughage to concentrate ratio of 73 to 27. The best results were obtained when crude fiber was 15 to 20 per cent, NFE 48 to 50 per cent, and TDN below 60 per cent in a pelleted ration. During this same period, Lindahl and Davis (1955) and Thomas et al. (1955) found that pelleting roughages increased ether extract, decreased crude fiber, made faster gains, and higher carcass grades when fed to lambs. Thomas, however, stated that these advantages were not great enough to cover the cost of pelleting.

The poultry industry for a long period of time had used pellets for convenience. It now experimented with the possibility of increasing gains. Alfred et al. (1956) reported increased gains in pellet-fed broilers over those fed meal. It was found that when the pellets were reground and fed the broilers showed greater gain than those on the unpelleted meal. Evidence indicated that the density of the pellet was not the only factor involved in better growth. This evidence also added weight to the growing belief that an unknown factor developed during the pelleting process.
Several authors have tried to summarize the results of the many trials and tests conducted to determine the value of pelleting. In the following reports, the benefits, values, and advantages of pellets, as they appeared in 1957, have been listed. A condensation of results obtained from various experiment stations has also been included. Hibbs and Conrad (1957), in summarizing the use of pellets, stated the advantages in feeding pelleted mixtures of roughages and concentrates with lambs, calves, and beef cattle to be:

1. Increased dry feed intake.
2. Greater efficiency of feed intake.
4. Faster growth.
7. Elimination of dust.

However, the cost of the pelleting process will have to be balanced against these advantages as well as:

1. The conservation of nutrients commonly lost in the field and in feeding when hay is made and in storage when silage is made.
2. The saving in labor resulting from mechanical handling and feeding with a minimum of water movement.
3. Reduction in storage space.
4. Better and more efficient animal performance resulting from increased efficiency of feed utilization, more
uniform availability of higher quality roughage and need
for less grain concentrates and protein supplements.

Esplin et al. (1957) summarized the results from experiments reported by
nine experiment stations. The results indicated a higher final weight,
a greater daily gain and less feed needed per pound of gain on the lambs
fed pellets. The report also stated that the average daily feed consump-
tion was the same for the pelleted and unpelleted groups.

In some of his more recent work, Neale (1958) substituted low
quality alfalfa roughage for the good quality roughage of previous trials
in an attempt to determine its value in a pelleted ration for lambs. It
was found that the group fed a mixture containing 80 per cent roughage,
10 per cent grain sorghum, and 10 per cent molasses required less feed
per pound of gain and the cost of 100 pounds of gain was less than when
a ration containing 70 per cent roughage, 20 per cent grain sorghum, and
10 per cent molasses was fed. A similar condition was found by Pope
(1959) in a trial using beef calves. In this particular experiment, a
1 part concentrate to 4 parts roughage ration was compared with a 4 parts
concentrate to 1 part roughage ratio. The 1:4 ration showed an improve-
ment from the pelleting process and increased the rate of gain over a
similar unpelleted ration by 23 per cent. The author felt that this was
in part due to increased feed intake, which was 2 pounds per day higher
for the pellet-fed calves, but it seemed unlikely, considering the nature
of the feeds used, that all of the increase was due to feed intake alone.

A majority of the trials conducted recently have attempted to deter-
mine the reasons behind the benefits derived from the pelleting process.
A few of the theories advanced by various authors are worthy of consideration. Weir et al. (1959), in a comparison of similar rations fed chopped, or ground and pelleted, to steers and lambs, found that again the greatest advantage from pelleting for both steers and lambs was obtained when straight roughage rations were compared. In an attempt to explain the reasons behind the increased feed intake and increased gain from pelleted rations, Meyer et al. (1959) concluded that the results of their work indicated that increased gains were due to the feeding of finely ground hay as pellets. This fine grinding caused an increased feed intake due to a faster passage of ingesta from the reticulo-rumen. The digestibility of lignin and holocellulose was not greatly influenced by grinding and pelleting, but nitrogen digestibility was higher for the pelleted hay. Lindahl (1959) also concluded that pelleting had little effect on digestibility of feed but appears to increase the rate of digestion and feed consumption. It was also concluded that pelleting could be used as a means of reducing feed requirements.

In concluding this section on the feeding trials, comparing pellets with ground rations, different levels of roughage and stages of roughage being pelleted, several similarities will be noted among the majority of experiments. Greater feed intake accompanied by a greater rate of gain is common in a great many of the trials. In conjunction with this, where different grades of roughage were used, the increased gain was more noticeable on the poorer grades. In comparing different levels of roughage to concentrate ratios, the greatest benefit was noted where the roughage content was the highest. The explanation of this
phenomenon varied considerably among the various authors. Some considered the greater intake alone as the reason for increased gain. Some considered the reason to be the more rapid passage of the material through the animal, caused by the finer grinding. However, throughout a great many of the trials, there appears to be a hidden or unknown factor that cannot be explained by any of the above mentioned hypotheses.

Mechanical Factors of Pelleting

In reporting the results of the various feeding trials, the exact mechanical formation or the temperature under which this formation takes place usually was not considered as a factor, with reference to the outcome. Several men, however, considered the type of pellet and its formation to have a direct bearing on the outcome of its use. There has been considerable speculation as to what mechanical considerations must be incorporated into the designing of a machine or machines that will produce a pellet that will give the maximum ease of consumption at the lowest production cost. A brief summary of the work done will be presented in order that the problem may be more fully understood. One further note of explanation may be necessary. With the growth of pelleting, the word "pellet" has come to mean only those cubes of small diameter, ranging from 1/4 inch up to 3/4 inch. Wafer or biscuit is the name given to the larger sizes which usually are made of long or chopped hay.

One of the earlier workers that considered variations in pelleting conditions was H. D. Bruhn (1955). In his experimentation, he produced
pellets with pressures of 4,000, 8,000, and 10,000 pounds per square inch. It was determined that a pressure of 4,000 pounds per square inch of cross section produces a pellet with a density of 40 pounds per cubic foot for number one alfalfa. A pressure of less than 4,000 pounds per square inch made a pellet that was easily broken up by handling. The 8,000 and 10,000 pounds pressure per square inch of cross section made pellets that were difficult for cattle to eat easily. It was, therefore, concluded that 4,000 pounds per square inch was the best pressure for the pelleting process from the mechanical standpoint. It was also observed that a pellet ejected from the press immediately after the pressure was applied tended to expand more after ejection and did not stand handling as well as a pellet held in the press for a short period of time. He also found that no supplemental binding agent seemed necessary and that almost any fairly dry material could be pelleted if enough pressure was applied. Bruhn concluded that alfalafs could be pelleted at 30 per cent moisture or less. At a moisture content of 50 per cent, the alfalfa acted as a fluid when subjected to high pressure in the pelleting cylinder. He found that the more leafy material present, the smoother, more dense the pellet formed. Using his experimental data, he found that pelleted forages could be stored in from one-fifth to one-sixth the space that was normally required for the same amount of chopped or long hay.

The main disadvantage of the existing pelleting equipment for making forage pellets previous to 1957, as summarized by Hibbs and Conrad (1957), was the inability to ground or chopped forage that could be left coarse enough to allow for optimum cellulose digestion in the rumen.
Further work by Bruhn (1957) resulted in varying pellet size from 3/32 inch to 2 inches in diameter to eliminate the need for fine grinding of the roughage. In conjunction with his work at this time, he formulated the opinion that in addition to the grinding, heating, steaming, cooling, and drying that takes place in the material as it passes through a pellet mill, there may be in some machines a change of state in the material due to the localized pressure exerted during the pelleting process. This theory lends further emphasis to the growing belief in the existence of an unknown factor.

By 1959 the pelleting of roughage had been replaced, in part, by the making of wafers. Further trials were conducted on the pelleting and wafering processes. Dobie (1959) found that in commercial pellet mills instantaneous pressures were measured up to 65,000 pounds per square inch. The resulting pellets had a bulk density of 40 to 45 pounds per cubic foot. This extreme pressure coupled with the necessity of fine grinding created a pellet that was too hard to be readily consumed by livestock. In an attempt to overcome this factor, an experimental wafering machine was designed to produce wafers that had a bulk density of 25 pounds per cubic foot or more. The wafers were made of chopped or long hay to relieve the necessity of grinding. Densities of 25 pounds per cubic foot or more produced pellets with good handling qualities, but cows preferred densities of under 25 pounds per cubic foot because of the ease with which the wafer could be broken up and consumed. Dobie determined the best moisture content for the hay to be wafered to be 15 to 20 per cent. He also found that little moisture was lost during the
wafering process because of the low temperature (110 to 120 degrees F.) and elimination of grinding. The proper pelleting moisture was also noted by Bruhn in his work during 1959. At that time, he found that alfalfa at six to eight per cent moisture was readily pelleted in a closed cylinder, but spraying with a small quantity of water or steam improved the pelletability of the hay. Further information was also presented regarding the factors that appear to have an effect on pellet expansion. These were presented as:

1. Pressure applied.
2. Hold time under pressure.
3. Moisture content of the material.
4. Other characteristics of the material itself, such as the kind of crop, stage of maturity, leafiness, etc.

To summarize the mechanical phase of the pelleting procedure, it is evident that no definite decision has been reached regarding the best form of the material to be pelleted. The proper pressure and temperature that will give the greatest ease of consumption yet produce a good handling product will also need further work. The pelleting or wafering process appears to have an unexplained effect on the material being pelleted that suggests a need for further study. The results of previous experimentation have shown that roughage, especially of poor quality, derives the greatest benefit from the pelleting process. Therefore, in considering roughages one must consider the digestibility of its most difficult component, cellulose and related carbohydrates. An understanding of the structure, both physical and chemical, will be necessary if a
possible explanation of cellulose digestibility is to be attempted.

Digestibility and Structure of Roughage Components

The existence of cellulose in plants and the degree to which it may be utilized by animals have drawn the attention of science for a considerable time. Schölknecht (1956) states that native cellulose, i.e. grass, green leaves, and annual plants, contain 10 to 25 per cent of their dry matter as cellulose. It has been found by Klug (1954) that cellulose may exist in two forms at the same time in the same plant. The crystalline form of cellulose is the perfect alignment of the glucose molecules into long chains and an ordered pattern. The amorphous form of cellulose is composed of deranged coiled chains or short chains folded together in a haphazard manner. Norkrans (1950) states that the degree to which cellulose is available or open to enzyme or bacterial attack is dependent upon the degree of crystallinity. He noted a correlation between increased degree of crystallinity and increased resistance against enzyme attack. Siu (1956) also noted that the degree of crystallinity affects the rate of decomposition by cellulolytic organisms. He therefore concluded that the size of the glucose chains or sub-units making up the cellulose polysaccharide influences the chemical behavior of cellulose. Stone (1958) found that attack by the cellulose enzyme was limited to regions of low lateral associations of the cellulose molecules and that any treatment of the cellulose which would increase the proportion of less ordered (or amorphous) regions would increase the extent of hydrolysis. The breaking of the crystalline chains will affect the
molecular weight of the chain. The degree of polymerization of a chain is stated to indicate the number of molecules of glucose that comprise the chain. An example according to Schildknecht (1956) would be a degree of polymerization of 3,000 to 4,000 for native cellulose. Battista (1950) reports that hydrolysis is a method of depolymerization. The conclusions of his experimentation on hydrolysis of cellulose showed that the weight loss on hydrolysis is dependent on the rate at which hydrolysis proceeds and the crystallization and crystal growth which appears to occur simultaneously with the hydrolysis. Mild hydrolytic pretreatments which favor crystallization of strained chains were found to be effective in reducing sharply the weight lost upon subsequent drastic hydrolysis. The drastic hydrolysis resulted in the crystallization of very short chain segments. This gives rise to crystalline nuclei which are acid soluble and are thus more readily removed during hydrolysis. Howseman (1959) found that the rate of decrystallization was sensitive to the type of structure produced from the ball-milling process, i.e. fine grinding. This decrystallization was accelerated by the presence of moisture and was greatest in an air atmosphere as opposed to a carbon dioxide atmosphere. The type of lattice that developed on recrystallization was dependent on the type of the original chains, the extent of the ball-milling operation and the conditions under which the material was allowed to recrystallize.

The problem of increasing the availability of cellulose is further complicated by the presence of a lignin covering over the cellulose fibers. According to Stallcup (1957), the reduction of digestibility due to increased amounts of lignin appears to be due to its role in the physical
structure of the plant rather than any chemical action or toxicity to the microorganisms of the rumen.

To summarize the problems presented by cellulose in making it more available for nutritive purposes, the complexity of the substance becomes obvious. For crystalline cellulose to be made available to attack by enzymes, the chains must be broken or weakened to increase the number of vulnerable points. As shown by Battista (1950), this alone will not insure increased digestibility, as cellulose is capable of forming crystals from short chain segments. These segments are themselves harder to digest than the amorphous form referred to by Klug (1954). The presence of the non-digestible product, lignin, also complicates any process attempting to change the form of cellulose. In many instances, as stated by Stallecup (1957), the presence of the lignin makes it impossible for the enzymes to attack the cellulose even when it is present in an amorphous form.
METHODS OF PROCEDURE

The literature review indicates the problems confronting the various investigators in the field of pelleting. An extensive and complex investigation would be necessary to cover all of the problems related to the formation of pellets. It is the intention of this work to restrict the research connected with pelleting to a basic investigation of the problems as they pertain to: (1) temperature and pressure of pelleting formation, (2) in vitro digestion trials, (3) infra-red spectrophotometer and x-ray diffraction examination of the pelleted and unpelleted materials, (4) "proximate" and lignin analysis of the pelleted and unpeletted material, (5) an examination of the pelleted and unpeletted material by a polymer process to determine the molecular linkage.

Pellet Composition and Formation

Before a comparison of the pelleted and unpeletted roughage could be made, it was necessary to locate a source from which the pellets could be obtained. A search of the commercial mills determined that it was impossible to control and/or vary the temperature or pressure with the existing commercial machines. To solve this problem, a series of pellet chambers, with a #519-CC-(C) thermocouple (Appendix A) in the base, were manufactured by the engineering machine shop at South Dakota State College. This thermocouple was capable of measuring temperatures over a range of minus 300° F. to plus 600° F. and accurate within .75 percent of a degree. Five modifications were made before a machine capable of withstanding high temperature and pressure was perfected (Figure 1).
Figure 1. Parts of Base Pellet Machine.
The pellet mold was incorporated into a Carver Laboratory Press (Appendix A) that had a maximum output of 20,000 pounds per square inch and contained hot plates capable of temperatures to 600° C. (Figure 2). With the resulting combination satisfactory control of the temperature and pressure could be obtained. Table I indicates the variety and stage of the roughage pelleted and the various combinations of temperatures and pressures to which it was subjected.

The procedure used in the manufacture of the pellets was as follows. Approximately five grams of the roughage sample was placed in the pellet chamber. The plunger was inserted and the machine placed on the plates of the Carver Press. The thermocouple was attached to a model 8658-B potentiometer (Appendix A) for a direct temperature reading. This potentiometer was accurate to within ±1.5° F. of the indicated temperature. When the required temperature was reached, pressure was applied with the press up to the desired pounds per square inch. This pressure was held for a two minute period, after which the maximum temperature was recorded, the pressure released, and the pellet extracted.

Seven pellets were made for each temperature and pressure group. The pellets were one square inch in surface area and approximately 1/4 to 5/16 inch thick depending on the pressure applied.

The material to be pelleted was first ground in a Wiley mill to 40 mesh. Figure 3 indicates the appearance of the roughage before and after pelleting.
Figure 2. Complete Pellet Machine.
<table>
<thead>
<tr>
<th>Plant Material</th>
<th>Pelleting Pressure - Pounds Per Square Inch</th>
<th>Average Temperature in Degrees Fahrenheit&lt;sup&gt;1/&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4,000</td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td>Range</td>
<td>119.8-120.7</td>
</tr>
<tr>
<td>Alfalfa-Brome</td>
<td>119.8</td>
<td>120.2</td>
</tr>
<tr>
<td>1st Stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa-Brome</td>
<td>120.0</td>
<td>120.5</td>
</tr>
<tr>
<td>3rd Stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Wheat</td>
<td>120.2</td>
<td>120.6</td>
</tr>
<tr>
<td>1st Stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Wheat</td>
<td>120.6</td>
<td>120.5</td>
</tr>
<tr>
<td>3rd Stage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Blue</td>
<td>120.2</td>
<td>120.1</td>
</tr>
<tr>
<td>Stem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Stage</td>
<td>120.7</td>
<td>120.1</td>
</tr>
<tr>
<td>Little Blue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stem</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd Stage</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>1/</sup> Average temperature of seven pellets prepared.
Figure 3. Roughage Before and After Pelleting.
In Vitro Rumen Fermentation

The in vitro fermentation experiments for obtaining cellulose digestion coefficients were carried out according to the method of Burroughs et al. (1950c) as modified by Bentley et al. (1954).

Two gram samples of the roughage to be tested along with the basal media (Table II) were added to the individual flasks. The flasks were placed in a thermostatically controlled water bath (38.0° ± 0.2° C.) and individually gassed with carbon dioxide as pictured in Figure 4. Rubber stoppers containing two glass tubes, one going below the surface of the media through which the carbon dioxide entered and the other being a short tube through which the gas could escape, were placed on the flasks. The flasks were thoroughly gassed with carbon dioxide and brought up to temperature before the rumen juice was added.

The rumen contents were obtained by the use of a suction pump from a fistulated steer. The contents were strained through four layers of cheesecloth and 40 ml. aliquots were added to each flask.

The digestion was allowed to proceed for a 48 hour period. Adjustments to the pH, 6.8, were made at four hour intervals for the first twelve hours. A saturated solution of sodium carbonate was used to adjust the pH.

At the termination of the digestion period, the flask contents were diluted with distilled water to 150 milliliters. The contents were thoroughly mixed and duplicate 25 milliliter aliquots were taken from each flask for cellulose analysis.

The aliquots were analyzed for cellulose content by the method of
**TABLE II. COMPOSITION OF BASAL MEDIUM FOR THE IN VITRO RUMEN FERMENTATION**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Milligrams per 150 Milliliters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urea</td>
<td>336.0</td>
</tr>
<tr>
<td>FeCl₃</td>
<td>4.4</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>7.5</td>
</tr>
<tr>
<td>Valeric Acid</td>
<td>10.0</td>
</tr>
<tr>
<td>Glucose</td>
<td>40.0</td>
</tr>
</tbody>
</table>

**Micrograms per 150 Milliliters**

| Biotin           | 20.0                           |
| P.A.B.A.         | 50.0                           |

**Mineral Mixture: (20 ml. used)**

<table>
<thead>
<tr>
<th></th>
<th>Grams per Liter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na₂HPO₄</td>
<td>5.65</td>
</tr>
<tr>
<td>NaH₂PO₄</td>
<td>5.45</td>
</tr>
<tr>
<td>KCl</td>
<td>2.15</td>
</tr>
<tr>
<td>NaCl</td>
<td>2.15</td>
</tr>
<tr>
<td>MgSO₄ · 7H₂O</td>
<td>0.582</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Final pH = 6.55

**Milliliters per 150 Milliliters**

| Innoculum       | 40.0             |
Figure 4. Apparatus Utilized for In Vitro Digestion.
Crampton and Maynard (1938) and were subtracted from the cellulose content of the initial sample of the material. The cellulose content of the initial forage samples were determined by the same procedure.

The *in vitro* cellulose digestion coefficients were calculated by the following series of formulae:

1. \( \text{Cellulose/gm. ration} \times 2 \text{ gm. ration} = \text{total cellulose} \)
2. \( \frac{\text{Cellulose/10 ml.} \times 10 \times \text{volume correction}}{} = \text{undigested cellulose} \)
3. \( \text{Total cellulose} - \text{undigested cellulose} = \text{cellulose digested} \)
4. \( \frac{\text{Cellulose digested}}{} \times \text{total cellulose} \times 100 = \text{per cent cellulose digested} \)

**Infra-red Spectrophotometer**

Comparisons were made between a pelleted and an unpelleted sample of the same material with the aid of a Beckman-IR5, Infra-red Spectrophotometer (Appendix A). To prepare the samples for a comparison two methods were used. These methods were the potassium bromide pellet and the mineral oil cell. For the pellet procedure, .02 of a gram of forage material and .5 grams of analytical grade potassium bromide were placed in an agate mortar and ground manually for 30 minutes. The resulting powder was placed in a 100°F. drying oven until moisture-free and stored in a desiccator. The material was then placed in a Beckman pellet die, under vacuum, and subjected to 20,000 pounds pressure per square inch in a hydraulic press. The resulting pellet was returned to the desiccator for moisture-free storage.
The liquid cell method required the sample to be ground to 100 mesh. A trial grinding indicated that this degree of fineness could not be obtained with an agate mortar. To reach the desired fineness, the material was ground in a ball mill (Appendix A) for 30 minutes. Approximately 0.2 grams of the powdered material were mixed with two cubic centimeters of mineral oil. Five drops of this colloidal suspension were placed in the liquid cell. Comparisons were made between the pelleted and unpelleted material. Comparisons were also made between the pelleted and unpelleted material and a mineral oil blank.

"Proximate" and Lignin Analysis

Five gram samples of the pelleted and unpelleted roughage were analyzed by the Agricultural Biochemistry Station at South Dakota State College for lignin, protein, and moisture by the following methods. Lignin was analyzed by the method of Norman and Jenkins as modified by Common. Protein was analyzed by the Kjeldahl method (official) as modified by Gunning (official) A.O.A.C.

X-ray Diffraction

The x-ray diffraction patterns (Appendix A) were obtained with a Spectron diffractometer. The x-ray beam (40 KV and 10 MA) from the copper target was filtered through a nickel filter. When the x-rays were impinged on cellulose, those rays striking the crystalline portion with three dimensional regularity were diffracted by some definite, but measurable, angle. These diffracted beams generate a cone of diffracted
rays at 2θ angle. The variation of the angles are simultaneously recorded on a graph in the form of peaks. Each peak is characteristic of a specific diffraction angle.

Hydrolysis and Crystallization of Cellulose

The holocellulose fractions were prepared by the Bennett method (1947). The three samples were taken from (1) unpelleted, (2) 120°F and 16,000 pounds pressure per square inch, and (3) 320°F and 4,000 pounds pressure per square inch of alfalfa-brome, third stage hay. These samples were sent to the American Viscose Corporation, Marcus Hook, Pennsylvania, for an examination of the molecular linkage. This fractionation of the samples was necessary to extract the lignin before an examination could be conducted. Earlier experiments indicated that the presence of lignin made a determination of the molecular linkage impossible.
RESULTS AND DISCUSSION

In Vitro Rumen Fermentation

A total of three complete digestion trials were conducted. The fourth digestion trial excluded the pelleted material of all three roughages at the 435° F. and 4,000 pounds per square inch level. This material pelleted at 435° F. had a burned appearance and odor. Because of its lack of digestion in the first three trials, it appeared that no further information would be obtained by further work with this material. Table III presents the averages of four trials for alfalfa-brome, western wheat grass and little blue stem grass. The figures indicate the average, total percentage of cellulose digestion found for the material at various temperature and pressure combinations.

It was determined by the digestion trials that the first stage, i.e. high quality, succulent, young forage, was least affected generally by the pelleting process. It was presumed that this was due to the fact that the unpelleted control was already so highly digestible that little improvement could be obtained by pelleting. In general, however, an improvement in digestion was accomplished by the pelleting of the third stage, i.e. late season, dry, stemmy material.

An over-all analysis of the data from the three roughages does not indicate a general trend or pattern that would hold true for a particular stage of all three roughages. It would seem, rather, that each roughage was peculiar in its behavior to the different variations of the pelleting process. It appears, however, that generally whether
### TABLE III. THE AVERAGE PERCENTAGE OF \textit{IN VITRO DIGESTION} OF ROUGHAGES

<table>
<thead>
<tr>
<th>Plant Material</th>
<th>Unpelleted Control</th>
<th>Pelleting Temperature - Fahrenheit and Pressure - lbs. sq. in.</th>
<th>120\degree</th>
<th>4,000</th>
<th>10,000</th>
<th>16,000</th>
<th>4,000</th>
<th>10,000</th>
<th>16,000</th>
<th>4,000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>300\degree</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>435\degree</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa-Brome</td>
<td>73.2</td>
<td>63.8</td>
<td>71.9</td>
<td>73.1</td>
<td>72.7</td>
<td>77.2*</td>
<td>74.5*</td>
<td>66.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Wheat</td>
<td>72.9</td>
<td>69.3</td>
<td>74.0*</td>
<td>75.1*</td>
<td>72.6</td>
<td>73.6*</td>
<td>69.0</td>
<td>70.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Blue Stem</td>
<td>63.0</td>
<td>65.7*</td>
<td>66.7*</td>
<td>66.8*</td>
<td>65.6*</td>
<td>66.9*</td>
<td>65.7*</td>
<td>60.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage\textsuperscript{2}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Third</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfalfa-Brome</td>
<td>56.6</td>
<td>63.0*</td>
<td>67.1*</td>
<td>66.2*</td>
<td>61.8*</td>
<td>54.5</td>
<td>53.8</td>
<td>61.3*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Western Wheat</td>
<td>57.6</td>
<td>61.1*</td>
<td>57.7*</td>
<td>59.1*</td>
<td>60.0*</td>
<td>62.4*</td>
<td>61.8*</td>
<td>55.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Little Blue Stem</td>
<td>54.2</td>
<td>63.9*</td>
<td>59.0*</td>
<td>60.0*</td>
<td>58.0*</td>
<td>58.3*</td>
<td>57.3*</td>
<td>46.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage\textsuperscript{3}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1/ Digestion averages of four trials.

2/ 1st stage is the high quality, succulent, young forage.

3/ 3rd stage is the late season, dry, stemmy forage.

* Increased digestion from the pelleting procedure.
a particular pelleting combination results in a positive or negative digestion, compared to the control, depends on the percentage of digestion of the unpelleted control. The higher the cellulose digestion of the control, the less improvement in digestion by the pelleting process.

An analysis of variance was applied to the resulting data. Comparing the pelleted against the unpelleted control, the F test indicated that no statistical difference existed between the samples at the five per cent level. This, however, was believed to be partially due to the limited number of trials conducted.

Figures 5 and 6 present an average digestion of the four trials for the pelleted roughage compared to the unpelleted in a graphic form. It may readily be seen by the use of the graphs that the third stage roughages, on the average, show an improved digestibility over the control. The third stage little blue stem grass shows the greatest advantage to pelleting, due to the low digestibility of the control.

Infra-red Spectrophotometer and X-ray Diffraction

The two methods are similar in their attempt to indicate certain components of the material being tested. The procedure used by the two methods in determining the components differ. Infra-red examines the internal construction of the material, producing the results on a special graph paper in the form of a pattern. Analysis by x-ray diffraction, however, deals with the total construction of the material. The components differentiated by this method are crystalline and amorphous
Figure 5. Graphic Comparison of the Digestibility of First Stage Unpelleted Alfalfa-Brome, Western Wheat, and Little Blue Stem Grass with Its Pelleted Counterpart.

1. Digestion of unpelleted control.
2. Pressure in pounds per square inch.
Figure 6. Graphic Comparison of the Digestibility of Third Stage Unpelleted Alfalfa-Brome, Western Wheat, and Little Blue Stem Grass with Its Pelleted Counterpart.
cellulose. These data are also recorded on a special graph paper as a series of peaks specific for the compounds contained in the material.

These graphs, by either method, are then compared to standards of known compounds in an attempt to determine the composition of the unknown being examined. The difficulty of analyzing the data derived from the two procedures is caused by the complexity of the material being tested. In a material composed of a large number of individual compounds or impurities, there is a tendency for compounds exhibiting similar wavelengths to mask the presence of each other. This masking makes positive identification of the compounds present extremely difficult. This factor should be considered in an analysis of the resulting data.

**Infra-red Spectrophotometer**

As indicated in the procedure, pellets consisting of .5 grams potassium bromide plus .02 grams of a pelleted roughage were compared to pellets consisting of .5 grams potassium bromide plus .02 grams of the same roughage unpelleted. This comparison was made using a Beckman-IR5 Recording Infra-red Spectrophotometer. This spectrophotometer differentiates between molecules on the basis of absorption or transmission of light. The light is picked up as an energy difference in the form of heat by a very sensitive thermocouple. This is then automatically recorded as percent transmission. The two beams of the instrument are referred to as the sample and reference beams. The pellets or liquid cells are placed in these beams for analysis. The pellet containing the more complex structure was placed in the sample beam and the pellet believed to be of simpler structure was placed in the reference beam.
If a difference exists between the two pellets, the differences are noted on the graph in the form of peaks. As a check to positively determine the pellet with the more complex structure, the positions of the pellets were reversed. If the original supposition was correct, the second graph will be an inverted image of the first, the line never falling below the original base line.

In the comparisons of the pelleted and unpelleted material, the pellet containing the unpelleted material was placed in the sample beam. In all cases the reversal of this proved the original to be true. It may be inferred from this, therefore, that a difference existed between the pelleted and unpelleted material. In all the comparisons made, the pellet containing the pelleted material was found to contain material of a simpler structure than that of the unpelleted control.

A second comparison was made using liquid cells. The material was suspended in a solution of mineral oil and compared in the spectrophotometer according to the same procedure used with the pellets. The purpose of this second comparison was to rule out the possibility of the roughage being affected by the pressure exerted during the formation of the potassium bromide pellets.

The accompanying figures indicate the results of the trials. Figure 7 indicates the differences between a comparison of the pelleted and unpelleted material in a potassium bromide pellet. Figure 8 presents the same material in a liquid cell. Similarities between the potassium bromide pellet and liquid cell indicate that no great change takes place in the material from the potassium bromide pelleting procedure.
Figure 7. Comparison of Pelleted (10,000 lbs. per sq. in.) and Unpelleted Third Stage Alfalfa-Brome in a Potassium Bromide Pellet.
Figure 8. Comparison of Pelleted (10,000 lbs. per sq. in.) and Unpelleted Third Stage Alfalfa-Brome in a Mineral Oil Cell.
An evaluation of the results obtained from the infra-red spectrophotometer was very difficult. The complexity of the material made it difficult to isolate and identify the various peaks on the recording graph. It did appear, however, that various combinations of free amino groups could be present. This was determined by a comparison with a standard indicating where the peaks for the various nitrogen compounds could be expected to occur. This theory was impossible to verify from the "proximate" analysis. The "proximate" analysis of protein only indicates total nitrogen present and not any breakdown occurring in the protein itself.

A study of the results from the graphs also indicated that the peaks for various aromatic compounds could be caused by the breaking of the cellulose chains or lignin molecule. To verify this conclusion, the holocellulose fraction would have to be pelleted and a comparison made between the pelleted and unpelleted fractions. This would eliminate many of the overlapping effects from the proteins and lipids present. The theory of lignin breakdown was not substantiated by the analysis results. As previously stated, this could be due to the complexity of the material, and a separation of the lignin would be necessary before any conclusive results could be obtained.

Many other groups possibly could be present from the location of the peaks. These include aldehydes, acids, alcohols, imines, aldehydes, esters, and ketones. It will be impossible to prove or disprove the presence of these compounds unless the whole plant is fractionated into its various components and independent analysis is made of each component.
X-ray Diffraction

An analysis of the results obtained by J. D. Sayre (1960) at the Ohio Agricultural Experiment Station indicates that no conclusive evidence exists to support the theory of structural change due to pelleting. Excerpts from the personal communication of Dr. Sayre summarize the results obtained from the X-ray diffraction study on first stage little blue stem grass.

In the pelleted sample, there is other material besides the cellulose which might cause distorted planes of atoms. And we do not know yet if such distortion indicates the beginning of digestion or break-down of the cellulose or not. Pure cellulose gives a pattern of three diffraction lines at 5.8A (15.2 degrees), 5.2A (17.0 degrees), and the main line at 3.8A (23.3 degrees). The finely ground plant tissue does not give these separated peaks but a broad rounded place over the range 15-22 degrees. As you can see ... This peak is always present indicating that among the material there is cellulose present. But for some reason, the separate diffraction lines do not show. Why this should be, we do not know, but it indicates a lack of true crystallinity or distorted spacings. Not nearly enough research has been done on this subject to know for sure.

"Proximate" and Lignin Analysis

The lignin and protein analysis results, determined by the Agricultural Biochemistry Station, indicate that no appreciable change exists between the pelleted and unpelleted samples. The small differences that do exist between the lignin values are believed to be due primarily to experimental error and not to any change caused by the pelleting process. An example of this would be the determined lignin value for the unpelleted third stage little blue stem grass was 10.42 per cent. The lignin values for the same material pelleted were 10.30,
10.89, and 10.67 per cent for the 4,000, 10,000 and 16,000 pounds per square inch (120° F.) respectively. It may be possible to determine a more definite lignin value if the lignin was first separated from the whole plant and pelleted in a pure state. This would make it easier to discover any actual changes that may take place during the pelleting process.

**Hydrolysis and Crystallization of Cellulose**

The results of the examination of the molecular linkage for the pelleted and unpelleted alfalfa-brows, third stage, by the American Viscose Corporation was submitted by Dr. Carl T. Herald of the Special Products Section. Dr. Herald urges caution in the interpretation of the results due to the presence of insoluble material still found in the holocellulose fractions. The results indicate that no degradation of the chain lengths was caused by the pressure-heat treatment of pelleting. The two pelleted samples show a close similarity in the number of glucose units present in the chains. However, both pelleted samples have a higher degree of polymerization than is found in the control sample. More specifically, the average degree of polymerization was 950, 1,040, and 1,030 for the control, 16,000 pounds per square inch (120° F.), and 4,000 pounds per square inch (320° F.) respectively. This would indicate that fewer open-end glucose units are available for bacterial attack in the pelleted material. They would, therefore, appear to be less digestible than the unpelleted control if the results of the experiment are correct. This would be contrary to the results obtained from the in vitro digestion trials.
SUMMARY AND CONCLUSIONS

A review of the literature pertaining to the problems encountered in the pelleting of roughage indicated that further work was necessary. A review of the literature revealed that considerable work had been done in the actual feeding of pellets to various classes of livestock. It also was evident that the mechanical factors affecting pellet formation were being extensively investigated. It was felt, however, that the various investigators had neglected the basic principles involved in the pelleting process. It was, therefore, the intent of this study to begin an investigation into some of the more basic aspects connected with the pelleting of roughages.

Seven groups of pellets were made, varying the temperature and pressure for each group, from first and third stage alfalfa-brome, western wheat and little blue stem grass. Using these pellets, various experiments were conducted to determine the chemical and physical structure of the pellets compared to an unpelleted control. These experiments included an in vitro digestion trial, structural analysis by the use of the infra-red spectrophotometer, x-ray diffraction, hydrolysis and crystallization, and "proximate" and lignin analysis.

The results of the experiments were to a large extent inconclusive. Variations in digestion were observed but, apparently due to the limited number of trials, did not appear to be significant when an analysis of variance was applied to the resulting data. The infra-red and x-ray diffraction procedures indicated that a difference did exist between the pelleted and unpelleted material, but the complexity of the whole plant
made it impossible to locate the exact cause of these differences. No appreciable differences were indicated from the results of the hydrolysis and crystallization procedure or from the "proximate" and lignin analysis data.

The conclusions to be drawn from the results of this experiment would initially indicate that further work would have to be narrower in scope. If any conclusive results are to be obtained, the whole plant must be divided into fractions and each fraction studied independently. This would eliminate, to a great extent, the masking of the results due to the various components. This would be especially true in the infrared and x-ray diffraction work and would also be very helpful in the other phases of this experiment. The inconclusiveness of this trial definitely indicates that further work is necessary on this segment of the pelleting process before an accurate evaluation of pelleting effects can be made.
LITERATURE CITED


Herald, C. T., American Viscose Corporation, Research and Development Division, Marcus Hook, Pa., 1959. (Personal Communication)


APPENDIX
No. 519-CC-(C) Thermocouple by:
Thermo-couple Products Co., Inc.
729 N. Addison Ave.
Villa Park, Illinois.

Carver Laboratory Press 17900-231 by:
Fred S. Carver Inc.
Summit, New Jersey.

8658-B Potentiometer by:
Leeds and Northrup Co.
Philadelphia 44, Pennsylvania.

Beckman-IR5 Spectrophotometer by:
Scientific Instruments Division
Beckman Instruments Inc.
Fullerton, California.

Spectron Diffractometer by:
Spectron, Ohio X-ray Inc.
Used by: U.S.D.A. Agricultural Research Service,
Crops Research Division,
Ohio Agricultural Experiment Station
Wooster, Ohio.

S. S. White Amalgamator No. 2 (Ball-mill) by:
S. S. White Dental Mfg. Co.
New York, New York.