

THE MEANING OF CONSOLIDATION

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IT HAS become customary for the Chairman of the Fundamental Research Committee to present an introduction to these fundamental research conferences in order to explain not only the aims and objectives, but also the plan of attack of the conference.

I have entitled this introduction *The meaning of consolidation*, because I believe that misunderstanding about the meaning of words is one of the main causes of confusion in the modern world. It always pays handsomely to decide what you are talking about, otherwise all your discussion may be wasted.

Before tackling the word consolidation, however, I would like to say a few words about another word that is prominently before us—the word *fundamental*. There is a lot of misunderstanding about this word and fundamental research is sometimes mistakenly placed in opposition to applied research. Quite recently, one of our trade journals stated that the proper place for fundamental research was in the universities: industry should concern itself with *applied* research.

As I see it, the logically separable categories of research are *pure* and *applied*, with *oriented* research as a possible middle category. Pure research is concerned with knowledge for the sake of knowledge, with no practical objectives whatsoever. Oriented research is oriented towards an area of potential application, while applied research is concerned with specific practical objectives.

All research, whether *pure*, *oriented* or *applied*, may or may not be *fundamental*, in the sense of probing down to the fundamentals of the problem. All good research must have a phase of such probing into the fundamentals, unless these have already been clarified by earlier work.

This is the sense in which we in this room, this week, are using the word *fundamental*. Very, very little of the work to be presented this week is pure research; some is oriented; most is applied. All, I hope, is fundamental.

Sometimes I hear people suggest that research workers in the paper industry have their 'heads in the clouds'. For those people, I recommend a

session with the dictionary—any dictionary—where they will find that fundamental means *essential; primary; important; that which serves as a groundwork*. It is with our feet on the ground, not our heads in the clouds, that we face this week's deliberations.

So much for the word fundamental. We must now return to *consolidation*—another very earthy word. When in 1961 I presented the introduction to the Oxford conference on the formation and structure of paper, I said that I had been able to trace no explicit reference to *structure* in any of the classic reference or textbooks on papermaking. Faced again with the same task, this time in the context of consolidation of the paper web, I decided to try the same procedure and duly looked up consolidation in all the appropriate books. With some astonishment and—may I say—with a certain simple pleasure, I could nowhere find a reference to the word. Not even the index of the transactions of the 1961 conference, *Formation and Structure of Paper*, gave even a sideways glance at consolidation.

Once again, let me make a disclaimer similar to that which I made in 1961: that omission of the word consolidation does not mean that there has been in the past no knowledge of the vital sequence of processes that result in a formed, consolidated sheet of paper. On the contrary, there are many references and there is much know-how on the processes of drainage and couching and pressing and drying and calendering, which constitute the succession of modes and phases of consolidation. As with *structure* in 1961, so with consolidation in 1965: the lack of explicit reference denotes a superficiality in our knowledge, a lack of probing in depth, a need to rethink our practical know-how in terms of logical scientific concept.

That *consolidation* was the right term to use in our choice of subject seemed implicit in the unanimity of acceptance when it was discussed in committee four years ago. Despite this, it may be useful to probe a little into the word itself to see how appropriate it is within the context of the chosen theme.

The word was selected originally as the one that could most adequately sum up and describe the practical effect and result of the papermaking processes of drainage, pressing drying and calendering, which follow wet end deposition of the pulp stock. I decided to check that selection against an authoritative definition of the word and duly consulted the *Oxford Dictionary*. The following definitions are recorded—

‘*To consolidate*—

1. To make solid: to form into a compact mass: to solidify.
2. To make firm and strong: to strengthen.
3. To combine compactly into one mass, body or connected whole.
4. To become solid or firm: to combine or unite solidly or compactly.’

Among the definitions of the word *consolidation* is included, 'Combination into a compact mass, single body or coherent whole.'

Truly, the *Oxford Dictionary* more than counterbalances the omissions of the papermaking textbooks, for here are listed explicitly all the practical and theoretical elements involved in consolidation of the paper web. There is both the *making* and the *becoming solid* or *firm*. There is the element of *forming*, and there is the element of *combination* (of component elements) into a *connected* or *coherent* whole.

Here, by clear derivation and implication, are the several types of structural change that transform the weak, soft, plastic wet web containing some 80 per cent of water into the hard, solid, dry sheet that we call paper, containing some 95 per cent of cellulose fibre.

It is important to distinguish among the different phases of consolidation and among the different modes of consolidation, involved or deliberately employed on the papermachine. It is a useful intellectual exercise to check these against the dictionary definition: to recognise here at the couch or the press an element of *forming* of a plastic mass; there at the press or in the dryers an element of genuine *compaction* of component elements, in one or other of the dimensional planes; here on the dryers and in the draws the *combination* of component elements to form a connected whole; then throughout, as a consequence of all these effects, the *making* and the *becoming solid* and *firm* of the artefact that finally emerges as a sheet of paper.

The various phases and modes of consolidation fall into two categories—those caused primarily by the removal of water and those caused primarily by the application of external forces. The two are frequently superimposed, sometimes automatically coexistent, but they are logically separable.

Water removal produces a succession of phases and modes of consolidation from the slice to the reel-up. The stream of stock issuing from the slice of the papermachine contains about 100 parts of water to one part of fibre, though even at that stage it has a genuine network structure. By the time it leaves the machine wire, containing now only 4 parts of water to 1 part of fibre, it has already been formed into a coherent body with a defined structure that clearly foreshadows the structure of the final paper sheet. This phase of consolidation has been achieved essentially by compaction through removal of free water, largely by gravity drainage and partly by suction.

Further compaction, through further removal of water by suction, occurs at the presses and, at this point, there also enters the compacting force of surface tension. In the drying section, surface tension compaction replaces water drainage as the dominant mode of consolidation, as more and more of the liquid medium is evaporated. Finally, when all the free water has been removed, the water dissolved in the cellulose begins to evaporate and a new

mode of consolidation enters—a fibre-to-fibre combination through hydrogen bonding ‘*to make firm and strong*’ the ‘*connected whole*’.

Externally applied forces are secondarily involved in the successive phases of consolidation by water removal: first gravity, followed by pressure and suction at the presses; later, even the phase of fibre-to-fibre bonding is assisted by the pressure of felts. Over and above this, however, there is a succession of other modes of consolidation caused primarily by the application of external forces, which mould and compact the web as it passes through the machine. Towards the wet end, conventional smoothing presses mould the surface of the wet web. On MG cylinders, pressure rolls force the mouldable web surface on to a smoothly polished surface and the forces of adhesion, coupled with hydrogen bonding, produce the typical polished surface of MG paper. On Fourdrinier machines, banks of smoothing rolls placed at strategic intervals up to the dry end can repeat the surface compaction process and, finally, dry calendering can close the sequence by moulding and polishing.

The theme of our conference is therefore highly complex and the final result of the sequence of phases and modes of consolidation cannot be predicted without a most complex analysis of the total situation, followed in due course by a synthesis based on superimposition of the complex sequence of events.

Although such analysis and synthesis must be the ultimate aim of our probing into the fundamentals of papermaking, I shall not claim or even hope that we can in this conference approach the ultimate objective. We can and do hope, however, to approach an understanding, at least qualitative and in some cases quantitative, of each of the main events in the sequence of phases and modes of consolidation. Our programmes has been designed to this end.

One of the objects of this introduction is to explain the reasons underlying the plan of the conference and of the chosen sequence of sessions and papers. Before doing so and as a preliminary to my explanation, I wish to link the theme, both historically and logically, with those of the 1957 and 1961 conferences.

In 1957, we considered the fibrous components of the paper sheet and the treatment to which they are subjected before being formed together into the fibrous web. In 1961, we considered the processes of formation and the structure of the web and sheet resulting from that formation. In both conferences, consideration of the focal subject required repeated reference to the properties of the finished artefact, the sheet of formed and dried paper; in each case, the scale and complexity of the subject made it necessary to concentrate our attention on a fairly well-defined section of the practical sequence of papermaking operations. Thus, in 1957, pulping and stock preparation was the practical focus; in 1961, wet end formation held our attention; only a

scant forward look could be given to later events in the papermaking sequence. To quote from my introduction to the 1961 symposium, 'Couching, pressing, drying, sizing, calendering: each of these processes leaves its mark upon the structure and character of the paper sheet and in due time must be considered. For the present, we have had to limit our field of interest. . . . Perhaps a future conference will carry the theme further, through the after-treatments and ancillary processes.'

The conference we start today is the conference to which I then referred, a logical sequence by reference to the chronological succession of events that constitute the practical making of paper.

It is a logical sequel in a second sense, also implied by the quotation above from my words in 1961. The processes of consolidation that succeed the wet end formation of the paper web are, as stated then, secondary determinants of the structure and character of the paper sheet. It can therefore be said that this symposium is truly a continuation of our 1961 proceedings in that the scientific focus of attention is still the structure of paper, even though the practical focus of attention has shifted forward. Indeed, the title of our present symposium might well have been 'The consolidation and structure of paper' had we been more consistent in our thinking.

For these reasons, it was accepted at an early stage that this third symposium would involve a considerable degree of overlap with the subject of the second symposium. For this, the organisers make no apology. The papers presented in 1961 were clearly forerunners of a concerted probe into the structural theme on the part of many active groups of workers. It is appropriate that this work, oriented whenever possible towards the hitherto unconsidered consolidation processes, should be presented to confirm, consolidate and carry forward the findings of our 1961 deliberations.

This continued attention to the structure of paper has nevertheless brought some problems in its train. In particular, it has not been easy to keep the attention of all our contributors focused upon the consolidation phase of the papermaking sequence. Regretfully, some otherwise outstanding contributions have been declined for this reason and, even among those accepted, it is clear that consolidation has sometimes been a secondary focus of attention for the contributor. It is hoped that deficiencies in this respect will be remedied in the discussions that will form a major part of our deliberations.

In working out the broad plan of the conference and in fitting in the various contributions, the committee encountered familiar problems of sequence and continuity. In some respects, the practical sequence of the papermaking operations seemed an easy and convenient guide to arrangement of sessions and papers, but superimposed on this was the need to move logically from general theoretical concepts towards the specific cases embodied in the actual

operations of papermaking and in the nature of paper as a final product. The problem was made still more difficult by certain types of contribution that, by their nature, covered a wide sequence of process and sometimes a wide range of treatment of experimental material.

After much consideration of the available material and of the nature of the theme, a broad plan was decided in which three main divisions were recognised—

- A. The basic concepts underlying the theme of the conference (sessions 1 and 2).
- B. The nature of the consolidation processes (sessions 3, 4, 5 and 6).
- C. Effect of the consolidation processes on paper properties (sessions 7 and 8).

A. Basic concepts

WITHIN this division, it was clear that there must be some preliminary consideration of the basic principles of heterophase bodies, especially of thin sheets derived from the felting or interweaving of polymeric fibrous components. The next step was to link these general considerations with the specific case of the cellulose fibrous web and, to do this, it was necessary to consider the basic properties of the component elements of this web.

Here then is the basis of the first day's proceedings, which start with Corte's paper on the structure and properties of heterophase solids, proceed through Mark's survey on synthetic polymers as sheet formers and open out into a sequence of papers concerned with the nature and properties of the cellulose fibres that are the main component elements of the object of our deliberations, the paper web.

In this set of papers, retrospective survey of the general theme of the cellulose/water relationship is allied to some elegant experimental observations of the physical changes involved during water removal. As yet, there is no direct consideration of the fibrous web: we are still concerned with sketching in the background.

B. The nature of the consolidation processes

WITH the scene thus set, the next session (the first of the four sessions of division B) moves into consideration of the earliest phase of sheet formation and consolidation. This is initiated by Steenberg's survey on the formation and properties of the fibre networks that already exist as definable bodies in advance of the first phase of water removal, which transforms these bodies

into thin sheets. The traditional view of papermaking tends to see the first phase of water drainage as a transformation of a formless slurry into a sheet that suddenly, *de novo*, exhibits describable structural character. The work described by Steenberg and his colleagues brings a refreshing new approach to the subject. It disposes of this inadequate view and shows a causal linkage between the properties of the pre-existing network and the properties of the newly formed web.

The later papers in this session carry still further the causal sequence of filtration and formation, from which there emerges a layered structure of fibres and water that is observably a sheet of paper *in embryo*. The first phase of consolidation has been completed.

The sequence of papers described up to this point is seen to be logical either in terms of theoretical considerations or in terms of the papermaking sequence. At this point, however, the tidiness of the pattern is somewhat disturbed, for, although both of the succeeding sessions are largely concerned with the pressing, drying and calendering sequence, several of the papers may seem to be only marginally related to this sequence. In addition, the distinction between session 4 and session 5 may not be immediately clear.

As spokesman for the committee, I must confess that it has proved somewhat difficult to fit all the papers into a tidy and logical pattern when, after three years of discussion and correspondence, the documents emerged into the hard light of day. As earlier indicated, in a few cases, the papers that came forward were so marginal to the central theme that regretfully we had to reject them. Others, although off-centre, were of a content and calibre that made it imperative to accept them. This accounts for some of the apparent untidiness.

Session 4 is logically centred around the papers by Pye, Washburn & Buchanan and by Page & Tydeman, explicitly concerned with structural and physical changes during pressing and drying. These papers deal directly with the phases of consolidation following immediately after the phase of free water drainage dealt with in session 3. Both are based upon direct observation of structural effects, illustrated by elegant photomicrographs. The other three papers in this session by Page, Sargent & Nelson, by Welsh and by Ihrman & Öhrn are not specifically directed towards consolidation by pressing and drying; the one is concerned with general observations of paper structure, the other two with the fundamentals of planar compaction; but the treatment of their content makes them most appropriate for inclusion in the same session. They are, like the other two papers, based upon direct observation of structural effects, with appropriate illustration and the four papers together constitute a valuable repository of recorded photomicrographs on paper structure. They are linked by treatment and content, as much as by theme.

At this point, I would like to dwell for a moment on the subject of planar compaction, which is dealt with by Welsh and by Ihrman & Öhrn. Through the accidents of commercial development, planar compaction (whether of paper or textiles or plastics) has become associated with certain patented processes and as a result has tended—I believe, wrongly—to be ignored in fundamental studies on paper structure and properties. The committee recognised at an early stage that this type of process involves a mode of consolidation quite distinct from those experienced in traditional papermaking and involves structural features of great intrinsic interest, irrespective of commercial application. We therefore had no hesitation in inviting contributions to open up this relatively unexplored range of phenomena. Similar considerations led to our encouragement of a contribution on the effects of high consistency refining upon the consolidation and structure of paper. In our view, commercial development of a process should not in any sense imply that it has no content of scientific interest: the contrary is generally likely to be true.

Session 5 is also largely concerned with the drying and calendering phases of consolidation, but the approach here is more theoretical and analytical, in contrast with the direct observation techniques of session 4. At first sight, the paper by Craver & Taylor, which leads off the session, may appear to be quite out of place. It certainly gave the committee a problem of location and may appear more appropriate to session 3, until one realises that it deals with the examination of cellulose pulp/water systems over the whole range of drying from 3 per cent solids content to total dryness. We trust that the conference will appreciate the dilemma and will accept the decision to place the paper in this session.

Session 5 is in several other respects a rather heterogeneous assemblage of papers, covering the effects of drying on fibres, the load/elongation properties of those fibres and including a sideways glance at thermal softening effects on the constituents of the fibres; finally, an analysis of dynamic consolidation during calendering. If time had permitted, some more logical breakdown of the contents of this session would have been appropriate, but every one of these papers has in any case a direct relevance to the central theme of our symposium.

Session 6 is the final session in the second division of the conference, the division that deals with the nature of the consolidation processes as such. It is concerned essentially with the influence of non-fibrous components upon the consolidation and structure of the paper web. It must start back at the early stages of consolidation and it leads through from fibre flocculation and network consolidation to the final emergence of the dry sheet. This is a miniature conference within a conference. In content and character, the three papers of this session are quite distinct from the rest of the symposium. Inevitably, there

is a marked review element in all of these papers, for they aim to sum up the salient features of a wide range of phenomena that are of vital practical importance in the formation and consolidation of the paper web. One of the main omissions of our 1961 symposium was the absence of adequate consideration of non-fibrous additives. It is hoped that this session will restore the balance and emphasise—rather belatedly perhaps—that papermaking is not a simple matter of fibres and water.

C. Effect of the consolidation processes on paper properties

IN the two final sessions of the symposium, we come to the third main division of the proceedings, dealing with the effects of consolidation upon the properties of paper: session 7 is largely concerned with mechanical properties and session 8 with optical, surface and interpenetration properties.

One of the noteworthy features of our 1961 conference was the outstanding session relating structure to mechanical properties of paper. Ever since the pioneer work of the Swedish school, this subject has had a remarkable fascination for paper research workers and we have felt it proper to maintain this interest by gathering together the various papers that became available for inclusion. The papers and discussion of 1961 on this subject were controversial, but gave clear indications that a definitive view was emerging about the basic concepts that control mechanical behaviour of the paper sheet. As a consequence, the committee deliberately asked for a comprehensive review of past work in this field. Hence, Algar's review paper, which provides an admirable background for further experiment and discussion.

This session includes four papers recording new experiment and theory, which must be tested and judged in the light of experience. They constitute a most interesting and diverse assembly. Two of the papers, those by Taylor & Craver and by Kallmes & Perez, relate to papers involving similar techniques and methods of approach already included in session 5. The separation into different sessions of the twin parts of these pairs illustrates one of the difficulties that faced the programme committee and the conference is requested to make cross-reference whenever appropriate.

Finally, in session 8, the relationships between consolidation and non-mechanical properties of paper are explored. Here, we come closest to the final end and purpose of our deliberations, the end and purpose that has already been debated by our distinguished guest, Prof. C. Cherry—the usage of paper for human needs.

At some future time, we may perhaps deal more adequately and more comprehensively with this tremendous subject. I use the adjective tremendous deliberately, for civilisation as we know it could not exist if there were no paper, above all for the purpose of communication. This final session can touch only

briefly on the fundamentals of the subject. Optical properties, so critical as indications of structure, so vital as controllers of usage, receive special attention in two papers from our Scandinavian visitors. A third paper touches on the practical theme of printability and the last contribution of all deals with fluid flow, which is common and basic to practically all forms of paper usage.

I am conscious at this point of the inadequacy of this concluding session: of the flood of unanswered questions that can be expected to pour in when we open our doors on to the field of paper use and application. Yet I am also conscious of the fact that we have rightly tried to concentrate upon a chosen theme, that we must necessarily exclude from this week's deliberations a vast range of interest and application. To recognise our limitations, in all senses, is essential. Let us recall again our central theme—consolidation of the paper web. It is a theme of far-reaching implications and consequences and I believe that the contributions before us are of high quality and significance in this field. I am also confident that the consequent discussions will be equally fruitful.

At the end of the week, there will be a last paper, hitherto unmentioned. None of us knows what will be in it, for it has not yet been completed. Upon Dr Gallay will fall a heavy burden and a challenge to his great talents: the task of providing a final summation and conclusion to our proceedings. I wish for him and all those who precede him a stimulating, provocative and successful conference.