Mineral Industries Experiment Station

Circular No.64

Discussion on Dust Explosions

Report of Conference Proceedings

September 4 and 5, 1962

College of Mineral Industries

The Pennsylvania State University

University Park, Pennsylvania

Circular of the
MINERAL INDUSTRIES
EXPERIMENT STATION

Number 64 - March 1963

DISCUSSION ON DUST EXPLOSIONS

Report of the Proceedings of a Conference
held on September 4 and 5, 1962
on the campus of

The Pennsylvania State University

---

under the joint auspices of

The University and The National Science Foundation

(Reporter: Dr. Robert H. Essenhigh)

College of Mineral Industries
The Pennsylvania State University
University Park, Pennsylvania

PREFACE

The meeting reported in these Proceedings, convened to discuss "Dust Explosions," was organized by the Departments of Fuel Technology and Continuing Education under the joint sponsorship of The Pennsylvania State University and the National Science Foundation. It was attended by 53 registrants (including 5 from Europe) representing 35 different organizations (see Appendix 1).

The General Chairman for the Discussion was Professor M. W. Thring (University of Sheffield, England) assisted by Mr. Donald Kingery (U.S. Bureau of Mines), Dr. R. Friedman (Atlantic Research Corporation), and Dr. Earl R. Mitchell (Department of Mines and Technical Surveys, Canada) who acted as co-chairmen for each of the three Sessions, as given in the Agenda (Appendix 2). As initiator of the Discussion, Dr. R. H. Essenhigh (Associate Professor of Fuel Technology) was named Conference Director and Reporter.

The objectives of the conference, as listed for the participants in a set of 8 points (see Appendix 3), can be described as "strategic" rather than "tactical": that is to say, it was an attempt to determine how many organizations and industries were concerned with the problem of dust explosions; how serious the problem was; whether sufficient research was being carried out to be able to cope with, and to abate, the explosion hazard; and, if not, how much more research was required and how this was to be organized and carried out. As a further guide to participants in the discussion, "An Appraisal" on "Dust Explosion Research" (reproduced as Paper 1 in Part III of this Report) was circulated beforehand that set out in general terms some of the problems involved, with an indication to solutions.

This report of Proceedings is set out in 4 parts. Part I is a short summary of the overall proceedings which may possibly be read as reflecting the particular bias and point of view of the Reporter. Part II is a Report of Sessions: in this, the Reporter has attempted to transcribe and reproduce the views and intentions of speakers, where named, as faithfully as possible; and for the rest to report objectively (though with personal views and comment interjected where specified) the general tenor and trend of the ensuing discussion. For any errors of fact, interpretation, or misrepresentation, the responsibility is entirely that of the Reporter. Part III is the collection of those papers presented at the conference of which the authors had been able to prepare written drafts, with the exception only of that by Mr. R. F. Schwab whose report is to be published in full elsewhere, and is only summarized (in Part II) in this Report. Certain other papers that had been previously published elsewhere were also made available to the participants, and these are listed in Appendix 4. Finally, Part IV contains the various appendixes referred to above.

ACKNOWLEDGEMENTS

In preparing and organizing this conference the Reporter gratefully acknowledges aid, assistance, advice, and encouragement from a large number of sources, and particularly to:

Dr. Eric A. Walker, President of the University, for his introductory speech welcoming the participants to the campus, before the opening of the first session, a gesture that was much appreciated;

Dr. R. H. Jahns, Dean of the College of Mineral Industries, for his address to the participants at the evening dinner on "The Changing Pattern of Research at Universities," which also was very much appreciated;

Mr. Floyd B. Fischer, Associate Administrative Director of the Continuing Education Department;

Mr. D. C. Jones, Director of the Mineral Industries Continuing Education Department; ably assisted by

Mr. R. B. Hewes, also of the M. I. Continuing Education Department;

and Mr. Bryce C. Gray, Conference Co-ordinator of the Continuing Education Department, who together (and particularly the two last) carried the main load of the background organization and administrative burden;

Dr. M. E. Bell, Director of the Mineral Industries Experiment Station, for assistance in a variety of ways, not the least of which was in connection with the preparation and final publication of this Report;

The Chairmen and speakers who did so much to give the conference a working platform and a tactical basis for the discussions;

The Director of the Safety in Mines Research Establishment (England) for provision of 50 copies of the Research Report No. 201, "Dust Explosions in Factories: A Review of the Literature" by K. C. Brown and G. J. James;

Mr. Tom W. Moodie, Chairman of the Instrument Society of America sub-committee on Electrical-dust Hazards, for copies of their status report S.R. 2 on "Electrical-dust Hazards";

Mr. Robert W. Olson for reprints from his paper in Mechanical Engineering for November 1961 on "Dust Explosions";

The Bureau of Mines for their enthusiastic and active support of the conference;

The excellent assistance of a number of secretaries, and notably Miss Theresa Fike and Miss Barbara Poorman; and

Finally, the National Science Foundation for the financial assistance without which the conference might well have foundered, and without which this Report would not have been possible.

R. H. Essenhigh
Conference Reporter

CONTENTS

Preface i

Acknowledgements ii

PART I: SUMMARY 1

PART II: REPORT ON SESSIONS

1. Opening, Prof. M. W. Thring (Chairman) and Dr. Hylton Brown 1
2. Session I: Facts and Figures, Co-chairman: Mr. Donald Kingery 3
3. Session II: Problems; Industrial and Academic, Co-chairman: Dr. R. Friedman 6
4. Session III: Action Co-chairman: Dr. E. R. Mitchell 12
5. Chairmans Summary and Closure 16

PART III: PAPERS

1. "Dust Explosion Research: An Appraisal" Robert H. Essenhigh 1
2. "Pioneering in the Study of Dust Explosions" Hylton Brown 10
3. "The Dust Explosion Problem" Donald S. Kingery and John Nagy 16
4. "Dust Explosions" P. Laffitte and R. Delbourgo 19
5. "Proposals for Experiments on Dust Explosions" Robert H. Essenhigh 22
6. "Electrical Dust Hazards" Tom W. Moodie: Status Report S.R. 2 of the sub-committee on electrical dust hazards of the Instrument Society of America 27

PART IV: APPENDIXES

1. List of Registrants 1
2. Agenda 4
3. Objectives of the conference 6
4. List of all papers available to the Conference participants 7
5. Vent Ratio Nomograph 8

PART I: SUMMARY

/ The quoted section numbers in the following refer to Part II: Report of Sessions. This Summary has also been reprinted in Fire Research Reviews and Abstracts: Vol. 5, No. 1, p. 55/.

Summarizing this Conference is by no means an easy task because of the diverse points of view presented. To reconcile these will clearly be the task of some future conference.

The original hope had been that the conference would result, at least, in a blueprint of action for cooperative research, or even perhaps to implement the blueprint with action itself (sec. 4.3). In the event, however, achievement fell far short of this for a variety of diverse and conflicting reasons (sec. 4.4) so, like a river estuary debouching through innumerable channels into the sea, impetus to action was lost.

To the extent, then, that the original objective of the conference - as originally conceived - was not achieved, to that extent the conference failed; but to the extent that an alternative objective was achieved - that of bringing to light all the obstacles to cooperative action, and indicating what action can now be taken - to that extent the conference succeeded.

The rest of this summary is, therefore, concerned with what appears to have been achieved; and what, therefore, should now perhaps follow.

(1) The starting point at least was unchallenged. The annual loss from dust explosions was estimated to be in the region of $75,000,000 at least, which was about $1,000,000 per explosion (sec. 2.3). In absolute terms the rate of loss is rising year by year, though whether this represents a rise or fall relative to the increasing size of the industries concerned was not decided (sec. 2.3).

(2) This loss occurred in all branches of industry where flammable dust was involved: coal mining, flour milling, feedstuffs and agricultural dusts, grain elevators, plastics and synthetic resin manufacture, power station boilers, and metals production and industries using such as aluminum and magnesium, etc. Of current incidents, about half were concerned with agricultural dusts (30%) and plastics (20%), but boiler explosions represent a currently significant hazard (sec. 2.3).

(3) To cope with this, the organization, both for research and for collecting statistics, is somewhat haphazard. About 25 laboratories are known to be currently concerned with research; but, without any central direction or central forum for periodic discussion, the potentialties for overlapping research in one area whilst leaving gaps unstudied in another, is very large. The exception to this, of course, is the Bureau of Mines, with its special area of coal dust explosions underground (sec. 2.4). Collection of statistics, so that developing trends can be spotted and watched, is also open both to overlapping in one area with gaps in another so that the overall picture may be distorted (sec. 2.3 and 2.4).

(4) The purpose of research, of course, is to obtain knowledge that then must be disseminated throughout industry. To carry this out, there stands between research and industry those who may be called the "field educators"; this somewhat amorphous but vital group is made up of such people as plant safety officers, insurance inspectors, etc.

(5) In reaching industry, the field educators provide the channel of communication between research and industry; but this only splits the education problem in two: when the field educators are themselves fully informed, they are able to reach industry with the necessary information; but the first requirement is to educate the educators (sec. 3.9).

(6) The technique of communication, therefore, has at least 3 aspects (sec. 4.5).

(i) In the first place, the field educators must themselves be trained, eg. by some appropriate course or set of courses in which research techniques, results and applications are fully explained.

(ii) Then, to maintain that training, new research results must be abstracted, interpreted, and cast into an appropriate form for immediate use by the field educators. There is no reason why the field educators should be expected to do the necessary interpretation of original research results themselves.

(iii) Finally, to maintain communication, adequate methods of dissemination are required: at present the Fire Research Reviews and Abstracts fulfill this purpose admirably, at least as a technical channel. The only query might be whether it is at present slanted too much in the direction of those in research, with too little at present for those who have to apply results in the field.

(7) A further problem concerns the audience; it does not necessarily follow that industry will wait upon the pleasure of the field educators. In the case of large firms which have experienced several incidents there is usually no problem as they have adequate safety precautions, supervised by safety officers. The trouble always is with firms who do not know of, or who do not believe in, the explosion hazard. If they have never had an explosion they assume their operations must be intrinsically safe, and see no point either in taking safety precautions or in supporting research (both of which cost money). Those that have had one explosion are inclined to attribute this to "bad luck"; they take precautions which they assume will be adequate, and also assume that their first explosion will also be their last. Again, therefore, they see no point in supporting research. Industry, therefore, is split into two groups: those who admit the explosion hazard; and those who do not (sec. 4.4 point 5.)

(8) Up to this point, those attending the conference were in general agreement: not unanimous, but adequate, and agreeing to differ merely on details. It was beyond this point that two marked dichotomies of thought appeared. The first can be described as an argument between "Education versus Research" (sec. 2.7); the second concerned the argument as to whether or not the different industries involved has a common ground in the subject of dust explosions: i.e., whether the problem was a single theme, with variations provided by the different dusts involved; or whether perhaps each dust represented an individual problem, and the common ground between dusts was small, or even negligible tending to zero (secs. 3.8 & 4.3). These two arguments were never resolved by the conferences; but they represent such extremes of thought that concerted action seems most unlikely until they are resolved.

(9) On the Education question, no one present disputed the need for more: the split in thought was whether any further research was really necessary. Those favoring education at the expense of research were quite convinced that sufficient was now known about dust explosions for adequate precautions to be designed for any conceivable case that might arise; all that is now missing is the application of available knowledge. This, it was commented represents either great faith, or great wisdom, or great bravery. Those who disagreed with the proposition seemed to be mainly those most closely connected with research; the Reporter must be included amongst those who disagreed most profoundly. This point is discussed in greater detail in sec. 2.7. Also very relevant is the set of 8 practical problems listed at the end of sec. 3.4, which some of the field educators, at least, would like to have answered. Also relevant is the nomogram, reproduced in Appendix 5, obtained in research reported at the conference (sec. 3.5), that can be used to predict vent ratios required in practical, industrial systems by scaling up from laboratory tests. If this new knowledge is of any value, it can only mean that previous knowledge was inadequate, and thus disprove the contention of sufficient knowledge, at least prior to the conference.

(10) The other point on which participants split, that of common ground, requires little more amplification. Since the basis of the belief was never explicitly stated - it appeared to be treated as being self-evident - it was never possible to refute it explicitly. It is, however, refuted implicitly by the Co-chairman's opening address to session II, in which he summarized the academic problems (sec. 3.3).

(11) A further mode of thought that came to light was the expression of a belief that there must be some significant difference in quality or caliber of thought between scientific and engineering research. Again, being stated as a belief, it was not possible to refute it explicitly. Though only a minor point, it was still sufficiently significant to be antithetical to acceptance of common ground in the problem (sec. 4.4 point 3).

(12) Conclusions - This set of opposed views is regarded by the Reporter as being largely a consequence of failure of cross-communication,

leading to ignorance of others points of view. To bring this out therefore justified the conference. What chiefly emerges from all this is:

(i) The need for a soundly-based training course for the field educators, covering all aspects of knowledge on dust explosions from the most fundamental to the most applied.

(ii) Creation of some adequate, periodic forum of discussion, either formal or informal, at which all those concerned with research on combustion and explosion of all dusts can meet: only then will it be possible to decide whether dusts present a single problem with variations, or a set of totally unrelated problems.

(iii) As a consequence of both the training course and the discussion forum, it is to be hoped that these will provide and promote the accurate and valid interpretation of past, present and then future research results; with the by-product, it is to be hoped, that well-presented interpretations of research results will become available for use by the field educators.

(iv) Finally: should any future action be contemplated to amplify and extend current research activities, the discussion of session II - with its survey of problems all the way from the most fundamental to the most applied - may provide the necessary ground plan for a properly balanced program.

PART II: REPORT ON SESSIONS

1. OPENING

Prof. M. W. Thring (Chairman) and Dr. Hylton Brown

The Chairman's opening remarks were concerned with levels of research in general, and how these could be applied to the specific problem of dust explosions. In this he set the scene of probabilities and possibilities in terms of the strategy of research, as follows:

Our objective could be described as conversion of an "imperfect" system (i.e., one in which explosions occurred) into a "perfect" system in which explosions were eliminated. This required: (1) the creation or generation of appropriate knowledge to be applied; and (2) application of that knowledge. Supposing that any necessary knowledge obtained would in fact be applied, then generation of the necessary knowledge required research; and the necessary research could be carried out at one of three levels:

(1) The ad hoc or "trial-and-error" type of research. In principle, this requires the empirical testing of a statistically representative set of all possible and conceivable conditions; and for each set of conditions, a method of suppressing or preventing flame has to be found, also by trial and error. For reasons of urgency, this has been very much the pattern on a limited scale in the past where specific explosions have generated limited research into curing or alleviating an immediate practical problem. Its disadvantage is its lack of generality and the uncertainty in extrapolating developed remedies to new systems.

(2) At the other extreme there is the perfect or absolute scientific method. This, however, is a very long term and, although it would have the advantage of complete generality on completion, it could probably be relied on always to provide developed remedies too late.

(3) Between these is the intermediate level of research in which partially-idealized experimental systems are created and tested on a large laboratory, or small pilot-plant scale. If such systems are sufficiently simplified to the extent that they can be examined over a very wide range of experimental conditions, in a reasonable length of time, then two sets of experimental programs can be developed from this as a "base", but moving in opposite directions regarding application: (i) using the "base" experiments as an empirical starting point, a step-by-step study may then be developed of more involved, complex, and divergent practical systems which can be completely though empirically explained in terms of the base experiments; and (ii) the "base" may also be used as a guide to the accurate identification and delineation of the most important of the underlying fundamental problems involved. These can be investigated by "applied research at a fundamental level", the objective being to explain the base experiments from first principles (also called "research in depth"). By keeping the base experiments not too far from application, extrapolation to practical circumstances is fairly rapid; and by simultaneously filling in the fundamentals, the level of confidence in the extrapolation is steadily and simultaneously raised.

As a first objective, to decide on the required base experiments from which to start work, it was suggested that a good starting point would be a classification of explosions by type. This would be followed by review of mechanisms, and existing theories and solutions. Finally, this assessment would be used to decide whether further action was needed, and, if so, what. This set of proposals therefore substantially paralled the topics of the sessions to come.

Dr. Hylton Brown's opening survey (Part III: paper 2) then provided a useful supplement to the Chairman's proposals. It dealt in turn with: the Historical Background; the first Dust Explosion Demonstrations; Early Publications; Early Research; Testing Apparatus; Unusual Sources of Ignition; and Methods of Prevention and Protection. One point made, that in the Reporter's opinion deserves emphasis, is the statement that, "There is much of value in these early reports that should not be overlooked in planning more advanced research"; and coupled with this is the comment that, "unfortunately, many of the early publications are out of print and available only in certain libraries. Perhaps it would be desirable to plan a volume of abstracts that would make readily available the principal data contained in these early publications."

2. SESSION I: Facts and Figures

Co-Chairman: Mr. Donald Kingery, U. S. Bureau of Mines

2.1 Objective - The stated objective for this session was to consider "the size of the problem in terms of human and economic loss; assessing current research facilities and requirements; and potential for expansion."

2.2 The speakers at this session, in addition to those previously arranged (papers 3 and 4: see Part III) included Dr. Mitchell, Mr. Nagy, Dr. Jacobson, Mr. Lee, Mr. Moodie, Prof. Thring, Prof. Spicer, Mr. Grabowski, Mr. Schwab, Dr. Thomas, Dr. Van Dolah, and others.

2.3 Pattern of Loss and Research - From the points made by the speakers the following general picture emerged:

(1) The size of the problem could be estimated in dollar losses as being around $75,000,000 p.a., representing about $1,000,000 per explosion.

(2) The number of plants handling explosive dusts was in the region of 35,000 to 40,000.

(3) The real hazard or rate of loss has been increasing over the last few years, but the relative hazard and incidence of explosions was presumed to be diminishing since the ratio of loss to the Gross National Product (as an estimate of the size of industry) was dropping. This, however, was challenged by one speaker who pointed out that most of the recent growth in the G.N.P. had been in the area of service industries which, as a rule, are not manipulators of hazardous dusts; in relation to the actual users in the basic and manufacturing industries, the real and relative rate of incidence may both, in fact, be increasing. This clearly requires examination.

(4) Of the total number of incidents reported, it was estimated that 30% were concerned with agricultural dusts, and 20% with plastics.

(5) It also appeared that many dusts were handled by operators who could be classed in two groups: large and small. Specifically, milling of flour was mentioned as an example. Sixty per cent was milled in small, individual family plants. The remaining 40% was milled by only three large companies. This complicated the problem of selling safety. A large proportion of the market was easily reached through a small number of large operators; the rest involved contacting a large number of small operators. This pattern was probably repeated in many other industries.

(6) To deal with the hazard, there were now about 25 laboratories known to be concerned with research on dusts and dust explosions, but it was possible that operations in a proportion were largely restricted for one reason or another to standard testing, with little opportunity or facilities for real research.

2.4 Data Collecting and Information - In presenting and discussing these points, it was also emphasized by several speakers that collection of data and dissemination of research results was greatly hampered by the lack of a central organization. The area most completely covered was undoubtedly that of coal mine explosions since this came under the aegis of the Bureau of Mines. The Bureau was in a position to collect adequate statistics of incidence, to carry out research, and make recommendations for safety measures. It was also in a position to make comparative tests of industrial or factory dusts, but these it did as a service to industry, as-and-when it could spare the facilities, since performance of this function was not a statutory requirement in the Bureau charter, or by law. In consequence, collection of data on industrial dusts was likely to be haphazard and possibly incomplete. Much of it was left to the agents and inspectors of the insurance companies, so overall there might be complete coverage of industry in collecting data, but there was no central organization for collecting, collating, and analyzing, to determine trends in hazards.

2.5 Testing - Availability of testing facilities was even worse. There were general complaints that: (1) the absence of a central testing agency made the quick assessment of hazard difficult; and (2) the absence of accepted standardized tests made interpretation erratic, even when test results could be obtained. This was in effect a plea for the development of new and better standards, for universal acceptance, that could give accurate information on the explosion potential of a dust under any specified conditions. Explosion potential has at least two facets: (1) probability of ignition, and therefore of an incident; and (2) the damage potential if ignition occurs. Although the Bureau and other research establishments had done much to standardize tests, these organizations still regarded the existing tests as less than satisfactory.

2.6 European experience - As a counterpoint to this, European experience was described by the appropriate speakers: in England for instance, the Factory Inspectorate were a government body charged with inspection, testing, collection of data (by law incidents have to be reported), and enforcement of the regulations (if necessary by closure of plant for non-compliance); and the Mines Inspectorate are a similar body whose responsibility is for incidents underground.

In France, the situation was greatly simplified by a very low incidence of explosions in general (see paper 4: Part III). Most incidents were in the coal mines; above ground, the greatest incidence was from sugar and flour. In these two last, static electricity had been found to be an important ignition source, but it was reducible by control of humidity. In this respect the speaker (Prof. Delbourgo) emphasized the high importance placed on education, firmly based on research knowledge; education was regarded as being primarily responsible for the low incidence.

2.7 Education vs. Research - The mention of education initiated a discussion that brought out two rival points of view of major significance which continued to run as a thread through the rest of the conference. It seemed to be generally agreed (as being self-evident) that prevention in the field required two things: (1) knowledge, obtained by appropriate

research; and (2) dissemination of that knowledge to the relevant elements in industry, ie. by education. The rival viewpoints that then emerged were:

(1) that we now had the knowledge; it needed only to be transmitted and applied in the field; and the failures now were failures in communication, information, and education. The Reporter's personal impression was that this point of view was held mainly by those working in the field.

(2) the opposed point of view was: that present knowledge was still far from adequate (see report of session II sec. 3.9 below); and, although dissemination throughout industry of what already was known would be immensely beneficial, that much more research was still needed because many apparently safe situations and systems should still at present be considered suspect. The Reporter's impression was that this point of view was held mainly by those engaged in research.

In analyzing these opposed points of view, it must be conceded that those research workers advocating more research (implying the expenditure of more money) have some degree of "vested interest" to defend; and this is not so in the case of those working in the field who feel that sufficient is already known. The Reporter's personal impression of this, however, is that those engaged in research are only too well aware of the limited conditions of testing, and limitations of test results. Extrapolation outside the dangerously narrow limits of experimental test, that has to be done under the pressure of practical situations in the field, is then done with an unknown margin of safety; and those in research feel, perhaps intuitively, that this margin is altogether too small or even non-existent. Precisely such an instance occurred a few years ago. An explosion was reported in a colliery in which the roadways had always been regarded as inherently safe because of the high percentage of moisture always present - so high that moisture could be squeezed out of a handful of the roadway dust. Only after the explosion were experimental tests reported on coal dust "muds", containing 40% to 50% moisture, proving that such conditions gave no margin of safety. The prior assumption of safe conditions had been based on an inadequate scale of testing and an unverified extrapolation.

3. SESSION II: Problems; Industrial and Academic

Co-Chairman: Dr. R. Friedman; Atlantic Research Corporation

3.1 Objective - The stated objective of this session was "Discussion of Research Tactics to Provide Solutions for Stated Industrial Problems."

3.2 Speakers - In addition to the Co-chairman's opening remarks, there were three other prepared speakers, after which the discussion became very general: speakers then included Dr. Jacobson, Mr. Nagy, Prof. Thring, Mr. Smith, Mr. Kingery; but many others participated.

3.3 Academic Problems - In opening the session, some of the academic problems were summarized by the Co-chairman in his introductory remarks.

From the purely research point of view we have heteroganous flame systems that we wish to understand as scientific systems. In principle, it should be possible to write down an array of differential equations that, on being solved simultaneously for different boundary conditions, will tell us whether ignition is likely. It should also then tell us: how any subsequent flame would then behave; what pressures it could generate; what speed it would travel at; and what conditions would have to be imposed to quench it. Dividing the problem into parts for component study, we have then four primary problems:

(1) Determination of explosion limits
(2) Determination of ignition requirements
(3) Determination of rate of propagation
    (i) at its intrinsic rate; and (ii) as influenced by turbulence, etc.
(4) Creation of methods of suppression.

It should be pointed out that "Determination" in research does not just mean "physical measurement of"; it carries also the general implication of understanding: that is to say, "determination" is only regarded as complete when satisfactory theories have been developed, and their predictions found to agree with experiment. This is necessary for two reasons: (1) it is a check on whether what is believed to be the parameter measured has, in fact, been measured; and (2) the total time and labor involved in testing would otherwise be prohibitive, if no theory exists, because of the wide variety of conditions and circumstances that would have to be studied individually. A theory that has been proved over a given range of conditions can be extrapolated, with considerable confidence and reliability, to conditions outside the test conditions (though the confidence level drops as extrapolation proceeds further away from the initial conditions.)

In attacking the problems, these have to be investigated as problems in their own right, but some degree of useful comparison may possibly be made by looking at them as homogeneous (gas) flames with additional elements superimposed; e.g.- Homogeneous flame - plus - (1) Radiation; (2) Devolatilization, etc.; (3) Gravity (sedimentation); (4) Particulate motion and behaviour.

These are additional elements that in gas flames are either of small importance or completely absent. What, however, stands out clearly by this comparison is the relative ignorance and dearth of information on the fundamental behaviour of dust flames as compared with gases. This in many people's view is the complete answer to those who believe that enough is already known about dust flames and explosions to justify no further increase in the research effort. This relative ignorance demands more research.

3.4 Industrial.- From the other side of the fence, Mr. Ventrone described and summarized some of the diverse elements that assisted in, or militated against, diminishing the hazard in industrial practice. In the first place it is self-evident, but still important to recognize, that a hazard exists because it is created. It is still a major problem in the field that the dust explosion hazard is still unknown or unrecognized by many manufacturers. A first requirement then is recognition and demonstration of the hazard. In recognizing the hazard, we recognize first that the two chief means of creating it are by grinding and milling. Allied to this is size reduction by breakage. The processes may be classed: (1) as primary when production of fines is an intermediate or end product in the manufacturing process itself; or (2) as secondary when production of fines is an unwanted, associated process, as in shaping by grinding, or in mining of coal. This means that there can be two approaches to explosion prevention:

(1) In the primary process, the hazard has to be accepted as something that must exist; so safety measures should be designed into the plant when it is constructed using flame traps; decoupling of processes; outside venting systems; safety locks; correct location of equipment - e.g. cyclone precipitators outside; use of "write-off" plant-construction etc.:

(2) In the secondary process, the dust is unwanted, so that the aim can be to neutralize, eliminate, or remove it if possible. This means that the above approach can be partially modified, for example: by redesign of plant or operations to reduce the production of dust; or removal of dust at the termination of a production stage, etc.

In addition, another empirical parameter that also influences the approach to control is the factor of plant size. On the basis of both experience and test information, it seems to be generally true that the best method of control in large systems is provision of suitable venting equipment; but in small systems, the better approach is removal of dust (when possible) and elimination of ignition hazards.

Concerning the questions of experience and test information, it is true that experience is often an invaluable guide to what might go wrong, but it is purely empirical, limited, and by no means infallible. Alternatively, test information has often substantiated and amplified experience, but too often it has given only relative information, and to that extent is only a form of refined, perhaps idealized experience.

Stemming from all this then, a set of 8 problems can be listed to which the safety officer in the field would like to have answers provided by fundamental research:

(1) We would like to know how laboratory tests and field operations correlate; at present the correlation is poor to non-existent.

(2) We require to standardize test procedures and prevention equipment, and determine what the tests really mean.

(3) We require tested, reliable, design information on location of prevention equipment.

(4) We require accurate information on how to prevent transmission of flame.

(5) We require more information on the precise function, operation-mechanism, and relative value of restricted and unrestricted vents.

(6) We require precise information on the real (fundamental) influence of particle size, moisture and additives.

(7) We require to know the meaning and real significance of rate of pressure rise.

(8) We require fundamental information on how to inhibit explosions.

3.5 Testing - Mr. Schwab, the next speaker, read a paper, to be published in the general literature in due course, reporting some experiments designed to fill some of the gaps, and to answer some of the questions listed by Mr. Ventrone. The specific concern was with venting; but associated data were obtained on: the influence of particle size, concentration, inert materials, and variations in the cloud conditions caused by variation of the dispersion pressure used to generate the cloud. Parameters measured were: the maximum explosion pressure; and the average and maximum rates of pressure rise.

In summary: (1) The maximum explosion pressure (which might relate to the intrinsic damage potential of the dust) was found to be affected only by dispersion pressure - the two were found to increase together, and then only up to an upper limit beyond which no further increase was found; the maximum explosion pressure was otherwise insensitive both to particle size, and to the presence of inert material when testing at the optimum dust concentration in an unvented system. (2) The rate of pressure rise, on the other hand (which might be related to the damage potential by impulsive shock), was strongly influenced, in opposite senses, by particle size and added inerts: the rate of rise increased with fineness, but was diminished by inerts. The rate of rise at any given concentration seemed to be primarily dependent on the specific surface of the dust, but was also influenced by concentration (indicating, possibly, that total surface area per unit cloud volume was the determining factor); it was also limited by the available oxygen.

Most important of all is the extraction of an empirical, but practically valuable, relationship between the rate of pressure rise and a parameter specifying the variation of maximum explosion pressure with vent ratio. As the vent ratio (vent area per unit volume of combustion chamber) is increased, the maximum explosion pressure diminishes empirically according to a simple power law of the vent ratio. On a double-log

plot the power index K is obtained as the slope of the plot; and the rate of pressure rise was then found to decay exponentially with this index-parameter, K. This correlation can then be used (1) to predict vented behaviour just from tests in a closed bomb; and (2) by means of a developed nomogram (see Appendix 5), to scale up the information to industrial equipment and buildings. The advantage of this is that vent ratios can be specified from closed-bomb laboratory tests that still give an adequate safety factor to the strength of any wall material used in constructing a container for industrial dusts.

3.6 Proposals - The final prepared contribution (by the Reporter, paper 5, Part III) concerned proposals for experiments to be carried out in the future, the objective being to provide a common ground at the strategic level for anyone concerned with research on this problem. In preparing the overall program, the principal dust in mind for investigation was that from coal; but much of the information obtained should be reducible to general principles, and then be generally applicable. The proposed experiments were divided into four groups: Group I, on Dust Behaviour is concerned with the physics of dusts and dust dispersion; Group II, on Combustion Mechanism and Flame Propagation is a sequence of experiments, working up from single particles, through plane flame systems, to an understanding of a true explosion flame; Group III, on Flame Suppression is concerned with the study of various systems of quenching flame and their mechanism of doing this; and Group IV, on Gallery Behaviour is the study of both flame and dust behaviour in a full scale explosion test gallery, and in piping.

In putting forward these proposals, one of the principal points made is both the need, and now the possibility, of designing experiments to test theories. Sufficient predictive theory now exists for this to be possible; and it is thought to be doubtful, on the other hand, whether further application of the empirical "accumulator" approach will provide much more than further tables of "facts" that are generally unrelated and uninterpretable.

3.7 Discussion - The general discussion that followed was somewhat discursive; it touched largely on details relating to the formal presentations, partly to clarify obscure points. In addition, supplementary information was provided on the state of knowledge in certain areas; specifically, the Bureau of Mines representative stated that a Report of Investigations was now available that was concerned with the relative importance and influence of particle size, moisture, ignition temperature, rate of pressure rise, etc., and much more information in addition to this was now being prepared for publication.

3.8 Interpretation and Understanding - In the course of the discussion, a point that clearly had been incipiently present all the way through was brought up explicitly: this was the question of the meaning and interpretation of data. It appeared that probably all those present had a clear cut idea in their own minds of what any given set of experimental "facts" must mean; but equally clearly, the interpretation of those facts varied widely, and sometimes critically, from person to person. Moreover, it was also clear that this variation of interpretation was not evident to many of those present. In one or two instances this led to a certain amount of talking at cross-purposes, indicating a lack

of cross-communication that appeared to exist between those working in different industries. In the Reporter's opinion, this was related to another problem that he had become aware of during the preparatory correspondence to organize the Discussion: this was the opinion, clearly expressed in some instances, that there was little or no common ground between those working on different dusts. This point of view (as reported below) was stated explicitly, and fully discussed, in the final session III; but in retrospect it would seem to have been a definite undercurrent which influenced the discussion on interpretation, and for that reason is mentioned in passing here.

So far as interpretation is concerned, the problem is that experimental behaviour is frequently the consequence of an unsuspected or unconsidered variable. This is often obscured further by use of convenient but sometimes misleading terminology. An example quoted was that of "Ignition Temperature." This traditionally is measured by some such device as an electrically heated furnace through which a sample of dust is projected. The original designers of this type of instrument, working between 1900 and 1930, were always careful to refer to the limiting furnace temperature as the "Relative Ignition Temperature." In the last 30 years, however, the term relative has been largely dropped, so that many users of published data believe these to be real ignition temperatures, whereas the true ignition temperature may well be (and in some instances has been proved to be) anything from 200° to 400° lower than the quoted figure. The danger of this misbelief is self-evident. As another example, tests have shown that the limiting furnace temperature increases with particle size. This has been misinterpretated as being an increase of the ignition temperature with particle size, whereas in fact the truth would seem to be that the true ignition temperature is unaffected, and what happens is that the particles just do not heat up so fast. Here again, misinterpretation could be dangerous. A final example discussed was the question of flame extinction by rock or stonedust in gallery tests. These show that, at some optimum dust concentration, a limiting percentage of rock dust is required to prevent propagation of flame to the end of the gallery. The exact reason for suppression has never been stated explicitly but is vaguely assumed or implied to be an upper limit effect whereby the rock dust acts as a heat sink. However, an alternative theory set out in one of the published papers, of which copies were available to the participants ("Combustion Phenomena in Coal Dusts": Colliery Engineering: see list, Appendix 4), showed that the experimental data could be adequately explained in terms of dilution producing a low limit effect; in addition, the thermal-sink theory of the upper limit was shown to be inapplicable as the quantity of stonedust available was deficient by a factor ranging between 2 and 10. Here again the alternative has not been proved but, if true, it means that the currently accepted legal requirements may in fact prove to be inadequate for all conceivable circumstances.

As a supplement to these points, the Bureau of Mines delegates pointed out that the choice of rockdust barriers viz a viz general rockdusting was primarily a matter of convenience and appropriateness to mining techniques. With regard to the rockdusting, the required percentages of inert were currently in the region of 80%. As a general comment, the Bureau were only too well aware that mining presented a

dust problem and hazard that was by no means yet mastered. Currently, three approaches were under consideration or in operation: (1) removing dust at the generation source; (2) binding the dust by some appropriate spray technique (e.g. the salt crust process); and (3) dilution with rockdust. Any new approaches, however, would always be open to exploration.

3.9 Education - The elements of this discussion brought out, by implication, an important aspect of the education problem that in the Reporter's opinion assists in clarifying the opposed opinions on the need for education rather than research, or vice versa. (discussed sec. 2.7 above). As the Reporter from reviewing the discussion now sees the problem. there are two communication gaps: the first is between the field educators and those they are educating in industry; and the second is between research and the field educators. If some of those engaged in research have themselves been caught in the pitfalls of interpretation (sec. 3.9, above), this is also likely to be true of the field educators who are faced with massive practical problems to which immediate practical solutions have to be found. Inevitably, therefore, time will force them to take published research data at face value, as they must do under such circumstances. If this then can lead unwittingly to error, possibly to dangerous error (as in the case of the wet coal mine), this is hardly the fault of the field educators. As a corollary, it also represents a degree of confidence in safety knowledge that may not be shared by those engaged in research; and such over-confidence is again hardly the fault of the field educators. On the other hand, those engaged in research probably forget that the unspoken degree of reserve customarily assigned to most research results by any experienced investigator is not normally transmitted in published papers.

The solution to this problem would seem to be education of the field educators in a 3 or 4 day course, with formal lectures covering the complete range of what is known, from fundamentals to application. Setting up such a course was proposed in the course of discussion for somewhat parallel reasons; one major advantage would seem to be that each side could possibly learn much from the other.

4. SESSION III: Action

Co-Chairman: Dr. E. R. Mitchell; Canadian Bureau of Mines

4.1 Objective - The stated objective of this session was "To discuss and examine possible courses of action, and ways and means to the defined objectives."

4.2 Speakers - This session was even more discursive and general than the previous ones, and there were many more speakers, particularly providing interjections and asides, than those noted, who included: Dr. Palmer, Dr. Miller, Mr. Jacobson, Mr. Putnam, Dr. Thomas, Mr. Moodie and Dr. Van Dolah.

4.3 Result of Discussion - It seems appropriate to record the summing up of this session at this point, before reporting the session, because the record of this session when read with hindsight then makes much better sense; without this it seems to be a set of confused cross-currents that achieved nothing. In fact, something of value was achieved, but not what was intended.

The original intention for this session had been to get participants to agree, if at all possible, on some common action, that would initiate more, and better coordinated, research, together with ways and means of implementing that action. In the event, it had become clear to the Reporter, as organizer, before the conference took place that this was an objective most unlikely to be realized. The reason for this is a consequence of the failure to meet the basic requirements for coordination: these are, that the parties concerned shall agree (1) that they have a common interest; and (2) their joint interests are best served by joint action. To the extent that this session, as originally conceived, was intended to produce joint action, or at least general agreement on what joint action was desirable, then to that extent the session failed. To the extent also that this was the key session of the conference, the conference also was a failure - at least in that particular. The point of divergence on which the session foundered was the initial failure to accept, or lack of belief by the participants, that they had a common ground. There were also tactical points of difference that influenced or reinforced other impressions, but the belief that: for example a coal dust explosion had little in common with an aluminum dust explosion, was clearly the chief reason for the initial failure of the intended objective.

Since it is now clear that no joint action will ever be taken until those in the different industries are convinced that explosions of different dusts are basically variations on a common theme - rather than, as is at present believed, being a range of different and unrelated themes - it is also now evident that the conference was bound to fail in its original objective. However, merely to have brought out into the open the primary stumbling block to coordinated action is a point on which basis the conference can be judged to have been a success. It is now known what common ground of agreement has first to be reached before it is even possible to talk about coordinated action.

4.4 General - In the discussion in this session, the overall background was, as described above, a general disbelief in the existence of a common ground - there were some exceptions to this, chiefly those most closely concerned with directing and/or participating in actual current research. Superimposed on this background, however, were a number of minority, but still important, cross-currents. Tracing and identifying them was by no means easy as they frequently interacted with each other, but some of the topics that could be identified included:

(1) The question of research versus education, as discussed above. This came out very strongly. Specifically, Dr. Miller speaking for the A.S.M.E. Power Committee on Boiler Explosions expressed the education view very strongly. He personally was commited to the view that current knowledge was quite sufficient; one thing lacking was an adequate and accepted terminology. To this the Bureau of Mines representative stated that they had developed and disseminated a satisfactory terminology.

(2) The need for a common discussion forum equivalent to that currently provided: (i) by the Combustion Institute for all combustion and allied processes; and (ii) the Conference of Directors of Safety in Mines Research, which covers all aspects of mining. In this, the explosion aspects are limited to phenomena related to coal dusts in mines. It was suggested that both the American Chemical Society and the A.S.M.E. already provided the necessary forum; but these two organizations clearly do not do this, at least at present, in the same special way that the Combustion Institute or the S.M.R. conferencesdo for their specialties.

(3) A minor, but evidently significant, mode of thought also became apparent when comments showed that certain of those present distinguished between scientific and engineering research. In particular, it seemed to be suggested that engineering research was something of a different, generally lower, quality or caliber. Why this should be thought to be the case was not made clear. In the Reporter's opinion, the whole field of research is essentially a continuum. For convenience, different extreme aspects can be described as "operating-level applied", or as "fundamental-applied"; and between these two, many other levels can also be designated. Any one level, however, must be reachable from any other; otherwise the lack of continuity can only mean that an absolute discontinuity in knowledge exists that will completely block the application of fundamentals to applied problems. If, on the other hand, the only difference is in quality of thought, this can only mean that some problems are more difficult than others; and frequently in this type of problem, it is the technological and engineering problems that require the higher quality of thought because of their much greater complexity. This dichotomy of thought is obviously something that must be eradicated if effective cooperative action is ever to be achieved.

(4) One organizational solution to the problem was described in an account given by Dr. Thomas of the Joint Fire Research Organization in England; this is an organization concerned with all aspects of research on unwanted fires. It has unique terms of reference: the funding is half from insurance companies and half from the government, but all the staff are government employees belonging to the Department of Scientific and Industrial Research. The research is undertaken on

behalf of the Factory Inspectorate (another and separate government department). The budget is of the order of $400,000 p.a.; the total technical staff is about 60, of whom 3 or 4 are working on the dust hazard. The organization also is coordinated with the Home Office, and other government committees dealing with specification of British Standards, and co-operation with concerned bodies such as Fire Brigades, etc. Another function is to collect statistics, e.g. on all dust explosions throughout the country; to use these to follow developing hazards, and to transliterate from dust to dust.

(5) Another barrier to joint action mentioned was the difficulty of "selling safety." Since loss from explosion is simply regarded as something that should not happen anyway, elimination of an economic or financial loss is not regarded as being equivalent to increase of a profit.

(6) The importance and need for better dissemination of information was one of the most important points discussed, and is amplified below.

(7) Finally, another point, also amplified below, was the contrasting experience on coordination of the American Petroleum Institute.

4.5 Information - The information question had already been examined in part in the previous sessions, but in this session another aspect was raised. Altogether, there appear to be two aspects of information, one "human" and the other "technical." Each can be subdivided in two:

(1) Human is concerned with (i) transmitting research results from the research laboratories to the field educators; and (ii) with further transmission by field educators to the safety officers and industrial operators.

(2) The Technical is concerned with (i) maintenance of adequate circulation and dissemination of research results throughout the literature; and (ii) interpretation of purely technical data into the form of safety codes, handbooks, and qualitative descriptions of flame behaviour for a qualitative understanding of the various phenomena. In other words, this is to provide the data that is to be transmitted by field educators to industrial operators.

So far as current action on these is concerned, it would seem that item (1) (i) represents a gap that, it has been suggested, can perhaps be filled by organizing Safety Courses for the field educators. These courses would describe and interpret past and current research results. If that action is taken, item (2) (ii) will then be largely taken care of by the normal operations of the field educators. This action, however, could be strengthened by construction and provision of simple demonstration equipment in which scale models of appropriate plant can be blown up. Additional help would be the making and provision of appropriate films by some central agency. Other more centrally organized measures might also be thought necessary to reach those in industry who at present are not aware of, or who do not recognize, the hazard, and who therefore would not attend demonstrations.

Item (2) (i) presents rather a different problem. Potentially effective action is being taken already by the Fire Research Reviews and Abstracts. There are, however, two associated problems: the first is simply the problem of organizing the collection and abstracting of published papers for inclusion in the abstracts. This would be immensely helped if authors of any relevant papers would send copies to the Editor, immediately on publication, for retransmission for abstracting. The second problem is again the one of audience: bringing the Reviews and Abstracts to the attention of those in industry who can make use of them. Another parallel problem of communication is that of the use of specialized reports such as Bureau of Mines Reports of Investigations and Bulletins, and the Safety in Mines Research Reports. However widely disseminated these are, they can never reach the general coverage of the standard technical and scientific journals. Dissemination of research results would, therefore, be greatly assisted by the periodic publication of outstanding, or summary, results in the general literature, rather than solely by the limited-circulation house publications. Such action might help to solve the problem of what is probably the biggest gap of all: item (2) (ii) - accurate interpretation into common-sense terms of the technical research results. Without closing this gap there can be no hope of success in the adequate education of industry because the field educators are not being provided with the tools to do the job.

4.6 Co-operation - By the end of the conference it was quite clear that, even accepting the partially-disputed agreement on the need for more research, the problem as a whole was so big that effective research could only be achieved by coordinated action. The proposal for such action then foundered on the failure to accept that the problem was one large single one, and not a multitude of unrelated small ones. The API experience in formulating a coordinated program, described by Mr. Putnam, therefore provided a most illuminating parallel. Briefly: the situation was that a number of firms found that they had common ground in trying to solve practical problems, mainly in connection with pressure-jet oil burners. Their initial approach was independent research; but when they were finally forced to accept that the magnitude of the problem presented a task beyond the possibility of solution by their limited research facilities and funds when operating independently, they accepted the need for coordinated action under the pressure of economics. This action started with that most important requirement: provision of adequate funds in a common pool; it then included provision of a full time coordinator to operate with a special "action" sub-committee. The first task of the committee was to break down the whole field into sections by means of adequate surveys; and these were then used as the basis for initiating research projects. Once started, the overall project never looked back; the surveys alone convinced any doubters of two things: firstly, the magnitude of the problem; and secondly, how little was really known.

In contrast, as the speaker pointed out, it is clear that in the dust explosion field, participants have not even reached the starting line - acceptance of a common goal. Perhaps, therefore, a complete set of surveys, on the lines of the API surveys, might perform the necessary function of convincing doubters of the existence of common ground. Thereafter, the API experience could then be used as a blueprint for common action.

5. CHAIRMANS SUMMARY and CLOSURE

Prof. M. W. Thring: University of Sheffield, England
(This summary was tape-recorded, and has been transcribed here from the recording with minimal editing.)

"Gentlemen: in summing up this conference, I am going to try to adopt two simultaneous postures: one as Chairman, and one as an outsider. As Chairman I can inject my own views of the conference into my summing up, but as an outsider this also enables me to say things, if I wish to do so, that could be quite contrary to your views.

I think that I could perhaps say that my qualifications for taking this stand are that some 14 years ago I set up the International Flame Research Foundation. This is an international organization dealing with quite a different type of problem, namely flames-when-you-want-them in industry. But the object then was, and still is, to try to fill in the fundamentals of those flames. The reason that we made it International was mainly that we could not get nearly enough money from any one country to do it; so we played one country against another until we got enough, and the Foundation now has an annual budget in the order of $150,000 p.a. I have mentioned this question of money and fund raising because the financial problem in the dust explosion field is almost identical.

Now, as far as this conference is concerned, I want to present my summing-up under three headings:

(1) Organization
(2) Data
(3) Experimental Program

5.1 Organization - Under this heading, we have had enough to make it clear that the subject we are discussing here is, of course, primarily one which is concerned with saving human lives and property. It is, therefore, a very important one, both morally and financially. In view of the sums of money which, as we have heard, are involved by loss every year in this country, then, even if we leave the moral issue out of account, I personally would say that there is no question at all that a country the size of the United States should be spending at least another $100,000 p.a. on this particular problem. I think that if you take the magnitude of the damage done by the explosions, that is really quite a small sum.

Now, looking at the moral issue, this is a very peculiar one. It is much easier, as everybody knows, to get millions of dollars to put a man on the moon than it is to get $100,000 to save lives. This unfortunately is true in our country, it is true in your country, and it is true everywhere else; but nevertheless, I think the clear conclusion from this conference is that the subject is so important to this country that an additional expenditure of another $100,000 p.a. would be - certainly not adequate - but certainly essential.

Another advantage of the existence of a moral issue is that cooperation and coordination are no longer dirty words, as they tend to be

because of the Anti-trust Laws in this country, but become quite legitimate procedures. In fact, I think there is a very strong case for international cooperation in this field, as well as the need for much stronger national cooperation and coordination than exists at the present time. It has been mentioned how many organizations already exist which have a more or less complete interest in the subject. These do, of course, overlap to various extents; but as an example of what coordination can achieve, the example we were given by Mr. Putnam of the experience of the American Petroleum Institue is a very good one. From it we can draw some definite conclusions as to how coordination could be improved in this field.

However, before I look at coordination, I would like to put another diagram on the blackboard. This time it is a diagram in time, instead of in space, and it is a very simple diagram (see Fig. 1). Here we are at this conference standing on the top of a small mountain that I shall call (A). Looking around, we see somewhere in the distance through the mist a high mountain (Z), which would be the complete solution of all the dust explosion problems of every kind. Now along the abscissa we have time; and we hope that in a certain number of years we will get from this small mountain (A), where we are standing now, to the top of this beautiful mountain in the mist (Z). The point of this diagram is that a lot of the things we have been talking about are really the means that we have to talk and work through to get from A to Z. Another very important point of the diagram is that whenever we are making this journey in the direction of Z, we must all the time keep the top of the mountain that we are trying to get to very clearly in our mind. On the way, there will be distractions. The pure scientists will tend to wander off into pastures where they have more fun, and the engineers tend to invent solutions to problems other than the one they are trying to solve.

Now, there are some more points I can put into the diagram. I think we could say, roughly speaking, research into the problem comes about the middle (say at K). Then, coordination and collection of existing data, along with sorting out the facts and publication of work already done, comes at the beginning (say at C). At the other end, we have, finally, a definite, comprehensive prospectus which will prevent anybody who reads and applies it ever having an explosion.

Textbooks come towards the end, say at T: textbooks on dust explosions, giving all the true facts. The whole question of education comes in, let us say at V, when once we found out the facts for teaching the people. In that connection, I would strongly endorse the suggestion that there is a need for organized short courses. These would cover all the existing scientific and technical knowledge about dust explosions which people can obtain; then, after a week or so, they are fully educated in this matter. This is one aspect of education.

However, my point is that there is a very definite path that has to be followed here. In this, one must recognize the existence of the different steps in the diagram, but they must all be steps moving in the right direction. If I might perhaps make a slightly more specific suggestion in this connection, it is my view that the steps that the API took of having an individual who was the coordinator, with probably a

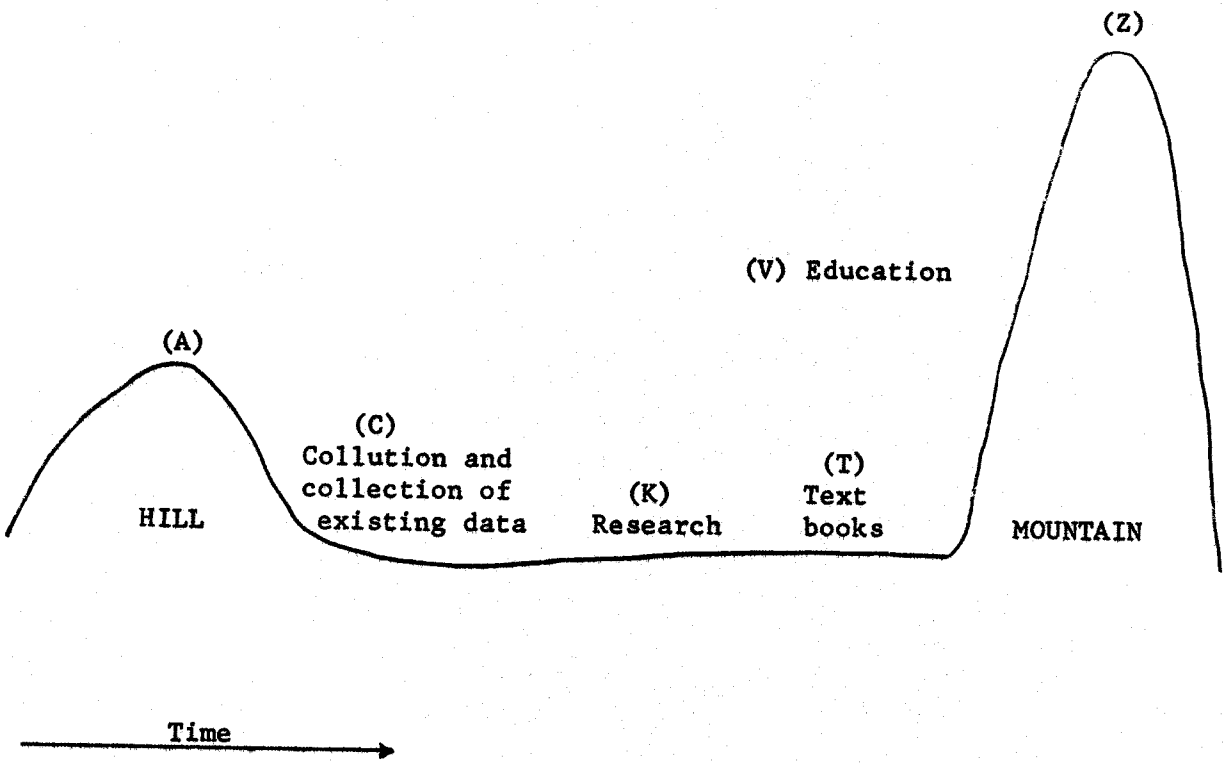

Figure 1. Illustrative diagram of research procedures and objectives. (M. W. Thring)

sub-committee specifically concerned with dust explosions (let us say, perhaps a sub-committee of the existing committee on Fire Research), this would undoubtedly be a great help in the right direction. As an aid to this, it is very good that there is already a suitable journal publishing good abstracts, but obviously there is not yet a sufficiently concentrated organization to help us in getting towards the ultimate goal.

5.2 Data - On this next topic, the question of data, we have, of course, many aspects. The collection of data on existing explosions would presumably be concentrated more if we already had the proposed organizational sub-committee. Now, as to the dissemination of this information, which is the whole question of education, I was particularly impressed myself with the gentleman who took a portable explosion apparatus into peoples offices and popped it off. I thought this was an excellent piece of work, and the more of that we can have, the better. But there are, of course, many other aspects of education, and one very important part of the subject is how much more has still to be done to get people to realize what a dangerous thing it is to have dust about in various places where they work - or even in their homes. But before we can start talking about data, we have to get it. Some exists, but not nearly enough, and to get more requires experiments, which brings me to my third heading.

5.3 Experimental Program - Well now, for this I described, at the beginning of this conference, the three ways in which you could go from the little mountain (A in Fig.1) to the big one (Z in Fig.1). For the argument, I am going to call them Levels 1, 2, and 3. Level "1" is the ad hoc Solution, or "suck-it-and-see." At this level it is clear, and I agree with this statement, that the problems of different industries are very widely different. In fact, the only thing common to them is that they mostly use air as the oxidant, but otherwise they are very obviously different. So, at this stage, I would put up what I would regard as a tentative classification of the problems.

Obviously, one of the things we have to do first is to agree on terms, but it seems to me that the discussion we have had thus far can give us a simple classification into four main groups:

(1) Underground, in coal mines: a wealth of good work has been done here over many years, and there is good work still being continued, though there is still much to be done;

(2) Above ground, we have the use of solid fuel: that is predominantly the use of pulverized coal systems, and can be subdivided:

(i) the internal problem of very fuel-rich conditions inside ancillary apparatus such as grinders

(ii) the problem of the combustion chamber itself

(iii) the external problem such as that of dust in the boiler house collecting on girders, etc.;

(3) Then there are non-fuel manufacturing industries; these can be given at least three sub-categories:

(i) plastics

(ii) flammable metals and similar materials

(iii) articles from special chemicals

finally,

(4) Carbonaceous materials (other than coal), mainly food and agricultural dusts; this includes grain elevator problems, flour, and in general the product of farms and everything that grows out of the ground.

Now, I don't think this is a perfect classification but, by and large, those are the main groups of industries where we have these different types of problems. Obviously, one of the things that a coordinating committee would do would be to set out this scheme in much more full and complete detail.

That now brings me to the details of the experimental program; but first of all I want to say that, I do think myself, that all that has been said at this conference does indicate very clearly that a lot more experimental work is needed in this field. This will definitely be necessary, in my opinion, before we can write the definitive textbooks and pages of rules that will prevent all explosions. Also, provided that in this experimental work we always bear in mind the objective of the top of the mountain, and not get sidetracked into pleasant but irrelevant pastures, it would contribute to movement in the right ultimate direction. This experimental work that I am speaking about is all on Levels II and III - the middle level and the fundamental level.

First of all, let us try to make a classification of the things we are looking for as possible means of preventing explosions. Again I have divided these into categories, of which I have three main ones:

(1) Eliminate Ignition
(2) Avoid Having an Explosive Mixture
(3) Coping With an Explosion if You Have Got to Have It.

Now, I don't know whether there are other categories, but perhaps when I subdivide these you will tell me if you think there are any. This again is something for our as-yet mythical sub-committee. Anyway I shall now discuss these one by one.

(1) To Eliminate Ignition, we have to eliminate ignition sources. Here we have problems of static electricity, electric sparks from actual electric circuits, frictional heat, slow chemical reaction, and chemical ignition such as the thermite reaction. What we have to do is to eliminate these various sources, but somehow I feel that this is rather a dangerous way of preventing explosions.

(2) Avoid Having an Explosive Mixture really seems to me the safest thing to do; I would rather not have any explosive about in my house. Under this heading we can again subdivide:

(i) avoid the presence of loose combustible dust. Here again there are several ways of doing this: (a) Good housekeeping - this can be difficult but is very important and it probably requires some kind of instrumentation method

of indicating whenever the good housekeeping is not being adequately maintained; (b) Reducing dispersibility - this might be done to prevent the dust that is loose from being blown into the air by an explosion by using some kind of adhesive; and (c) the opposite of adhesive, preventing the dust from adhering, particularly on vertical faces, by the use of some anti-static agent. All these have been mentioned, of course, in connection with mine explosions, but they are applicable to other systems also.

(ii) make the mixture non-explosive by Inerting. This again has been used extensively in coal mines, mainly by the use of stone or rock dust, but water has also been used, and there are probably a good many other possibilities also that can be used outside the coal mines. A current one, as we have heard, is the prospective use of water for inerting in boilers after a flame-out.

(iii) similar to inerting is the Inhibitor, which actually makes the mixture non-explosive by inhibiting the chemical reaction. A great advantage of this is that it often needs only very small quantities of material as compared with the quantities required for inerting. However, we need research to find out what materials will work.

(iv) finally, we can inert the gas phase; for example, as was mentioned in connection with the flushing out of conemills, the object is to eliminate oxygen so that you get outside the explosive range. You may have heard of the method being used now in England for putting out fires in warehouse basements by pumping in a mixture containing only 5% of oxygen from the combustion chamber of a jet engine, so that the combustion can no longer be supported.

(3) Now, in Coping With the Explosion, we have already heard of:

(i) venting

(ii) the use of thick container walls

and (iii) the use of baffles, traps, and suppressors, or methods of isolating the explosion in one part of the system, and not letting it spread through the rest.

Finally, on top of this all, I think we want to add an "I" for Instrumentation, because always we want to have good accurate instruments to tell us when a dangerous situation has been created.

Finally then, having attempted to classify the methods of preventing explosions, I will put forward to you my ideas for an experimental program that I have formulated largely as a result of this conference. I hope I interpret your views correctly if I place this program as being needed at Level II, that is the intermediate level, rather than at the completely fundamental level. In splitting the problem in two at this level, you still have the different elements mixed together, but you have to have a good understanding of the problem at this intermediate level if you are to get results that are valuable.

Now, in classifying the experiments, I would say that four categories are needed here:

(1) The Development of Instruments, particularly instruments for indicating when a dangerous situation is arising;

(2) The study of Models and Model Laws - I will say a bit more about that in a moment;

(3) The Use of Miniature Explosion Apparatus - there is still a lot of uncertainty in this because it still contains all the complex effects of explosions, but we had an excellent paper yesterday from Mr. Schwab describing what can be done in this field in spite of the complexities and uncertainties;

(4) The Actual Testing of Different Dusts to find out just how explosive they are; this obviously is work that needs to be done by an organization which is prepared and equipped to do it. In my opinion, the more closely that testing work can be done in conjunction with research on these lines, the better, because the test used on the dust is much more likely to be a valid test if it is done in conjunction with this kind of research. The coordination of these different lines of research is terribly important.

Just to go back now and simplify point (2), what I have particularly in mind here are two things. The first is that it is very necessary to do experiments in two pieces of apparatus, one of which is, say, 10 times the linear dimensions of the other, and then to see whether the results obtained with the small one still hold, and in what way they hold, when you come to the big one. In both these systems, one would have to study particularly the question of venting, and the question of pressure build-up. For example, one must scale up the systems exactly in proportion to the pressure build-up; and the scale-up must be by the absolute scale of the absolute pressure ratio (which is: the final pressure/the atmospheric pressure). Then there is also the question of the surface proportions of the apparatus to be brought in; this is a very important variable. One must do the experiments on the two scales as far apart as possible, and study at least some of the variables on both scales to see how far the small scale apparatus gives you results having any meaning at all.

The second aspect of model work, of course, is the use of models of an appropriate size to study explosion risks in complicated systems in complicated geometry. For example, in the questions of venting, and of different resistances in the venting system because of different shapes, there is a good deal of work going on in Britain at the Safety in Mines. In one particular system, geometrical models have been used for studying the effects of explosion when you get some methane in the top of a cavity in the roof of a mine roadway. In practice what happened was that combustible collected there, with air underneath; then the whole thing blew out, and projected a flame running all along the gallery although there was no flame in the gallery to start with. Models are being used to study actual situations, such as this one where an incident actually occurred, or others where incidents might have occurred. Using this type

of geometrical-similarity model is a very important use of models; but of course, pointless until you know whether your model laws are satisfactory, or whether the results you get have any meaning. This again calls for definitive research.

Well, finally, I will just conclude with a word about Level III research as I see it relates to the subject from what I have heard at this conference. This Level III, of course, is the study of the separate physical and chemical laws and mechanisms, separated as far as possible from each other. Here, of course, we have a nice program for the academic scientists for at least 20 years in the field of dust explosions: there is the whole aero-dynamics of dust explosions; the further study of flame propagation in this particular type of system; the study of ignition; and the study of the catalysis and surface reactions of individual particles under each type of very rapid propagation conditions. That, it seems to me, is what clearly follows out of this conference as being the kind of work that needs doing.

And that, I think about sums up what this conference has shown up as being the kind of work that needs doing. All that needs to be done, now, is the work!"

Paper 1: Dust Explosion Research: An Appraisal

by

Robert H. Essenhigh, Associate Professor of Fuel Technology

Introduction

Research on dust explosions has been in progress intermittently for 100 years and continuously for more than 50; but explosions in industry, both above and below ground, are still responsible for more human and economic loss than should be tolerated. What to do about this is simple in principle: research is needed to give us so complete a knowledge of dust flames that the probability and magnitude of an incident under any conditions can be accurately forecast, and fully adequate precautions taken beforehand.

To implement this is rather more difficult. The required degree of knowledge is far beyond anything we have at present: real "Know Why" of explosion behaviour scarcely exists; and the "Know How" of prevention is not much better.

It is believed, however, that this situation could be transformed, perhaps within so short a period as five years, by a carefully prepared and co-ordinated program of research. This appraisal is therefore concerned with the background to, and preparation of the strategy of such a co-ordinated program.

Historical Background

That such progress in so short a time should be thought possible in spite of the apparent relative failure of past research may sound surprising, but it is the very failure of the past work that has brought into perspective the full complexities of the total problem and has provided the foundations on which an effective co-ordinated program can be built. The trouble of the past was the tendency in any given research program to concentrate on one particular aspect of explosion behaviour; this tendency was a consequence of the failure to appreciate that the complex problems presented by dust explosions demanded a complete series of inter-linked investigations. The concentration primarily on one aspect or another, to the exclusion of the rest, would be like a mechanic faced with a motor car for the first time who then assumed that the dominant and most important part was, let us say: the engine alone; or the steering alone; or the transmission alone.

The Pulverized Coal Problem - This tendency to exclude and select in both the research and its interpretation is seen particularly clearly in the closely related field of pulverized fuel (P.F.) combustion (which at the combustion mechanism level is, historically, a direct follow-on from the earlier research on dust explosions). As useful lessons can be drawn from this parallel work, which is also closely relevant to background to explosions, what follows here is an outline of the development of the P.F. research; this also leads to a blueprint for action on dust explosions.

In the first (explosion-research) phase, dating from the late years of the last century to the early 1920's, the work was carried out mainly by chemists investigating the chemical behaviour of burning dusts, notably of coal; and the interpretations of this work naturally were almost exclusively in terms of the chemistry of the systems. This first period, called by Thring the "Bone and Wheeler" era, was only partially successful, and it was followed in the decade of the 1920's by the physical studies of the Nusselt-Rosin era. In this second period the factors dominating the reaction system were assumed to be primarily physical, for example, diffusion in micromixing; since this assumption required that the actual reaction had to be so fast as to be relatively instantaneous, it meant that the chemistry of the system (and therefore much of the previous work) could be ignored entirely.

Parallel with that development was the rapid growth through that decade (1920 to 1930) of commercial P.F. systems, with the consequence that the next research group to become involved were the engineers. Experimentally their influence became apparent in the following decade (of the 1930's), as a consequence of their studies in heat transfer, a leading figure in this being Wohlenberg. Once again development proceeded with surprisingly little reference to the previous work (of the chemists and physicists). The new work was by no means carried out in isolation but the tendency was to measure heat transfer as the principal flame parameter, with too little attention given to the flame behaviour. As this again was only partially successful it gave way eventually in the immediate post war years to the studies of the last single group, the aerodynamic school of the applied mathematicians. On their assumption, macromixing was assumed to be dominant, as expressed by the phrase: "If it has mixed, it has burnt." This was successful when applied to large gas flames, but it is far from true of dusts.

Superimposed on this pattern of development was a further complicating factor: the failure on the part of many research sponsors to appreciate the different emphasis placed on objectives and methods by the scientists doing the applied research on the one hand, and by the industrial engineers applying the results of that research on the other. A case in point is provided by the heat transfer measurements of the engineers. From the industrial, or engineering, point of view one practical objective is to transfer the maximum heat in the minimum volume at maximum efficiency. In consequence, the heat transfer was therefore made (erroneously) the central objective of the research. This approach produced much empirical data of some degree of practical value, but only at great expense in time and money. It frequently required direct measurement on the actual boilers at a one-to-one scale and, as effective extrapolation to other systems was sometimes little more than inspired guesswork, it was only partially successful. It took some time to realize that to treat an industrial problem scientifically often requires an inversion of emphasis. From the scientific point of view the central problem is the combustion, not the heat transfer; but as the heat transfer is required for full understanding of the flame behaviour, we then find that the solution to the central practical problem appears as a boundary condition in the solution to the scientific problem. This inversion of emphasis often gives the impression of an apparent irrelevance to research proposals designed to solve applied problems. As this is something that many industrialists have not always

appreciated, it has created in many instances a contempt for fundamental or "long-haired" research.

This is also well illustrated in another problem that currently is of dominant importance commercially: that of ash behaviour. Here again research emphasis has been on the ash, rather than on how the ash reciprocally influences the combustion mechanism. Once again the result has been the production of a mass of empirical and largely conflicting data. Not until the ash is treated as a modifying component of the combustion system will its behaviour ever be understood. This inversion of emphasis has been called the "back-door" approach, and is by no means new: for instance it was used by Archimedes in his famous "crown" investigation; in this, the scientific study of densities by his newly-discovered Principle of Hydrostatics provided, as a boundary condition, the required information of practical importance (that the golden crown had been adulterated).

Development of Research Strategy - In the research on the P.F. system work did not stop with the relative failure of the aerodynamic approach. Of course, in the four different consecutive eras, dominated in turn by the chemists, the physicists, the engineers, and finally the mathematicians, the concentration of attention (though by no means exclusive) was nevertheless probably inevitable. Individuals having a specific training are bound to look at problems from the viewpoint of their own specialized knowledge, and this all too often covers no more than their own specialized training; also, the associates they will attract are likely to be of a similar training. Such an approach is bound to create and perpetuate blind spots when applied to any technological subject, particularly one such as combustion that cuts across so many different formal disciplines. It was then the appreciation of this point by those working in the industrial combustion field (of P.F., oil, and gas) that finally cleared the way to the co-operative work of the International Flame Research Foundation, and thence for the subsequent dramatic development in real understanding of P.F. combustion mechanisms and behaviour. Just how dramatic this development has been in the P.F. field is still not generally appreciated as much of the most recent and important work has yet to be published.

The key to this rapid development was the appreciation that no one of the elements of the problem - the chemical kinetics, heat transfer, diffusion, mixing, etc. - could be identified as being dominant, to the practical exclusion of the rest. As a corollary it therefore followed that if all elements were important, then work was required by people drawn from a complete range of different specialized trainings, even though they might be working either individually or in groups. This, in turn required a breakdown of the problem into a series of interlinked and co-ordinated programmes, so arranged as to make the best use of the specialized knowledge of any one individual investigator. Figure 1 illustrates one such typical breakdown, of the P.F. problem, developed in this instance to provide the strategic basis for a tactical guide to action (and also incidentally to meet the requirements of the sponsors of the research program involved for: "Applied Research at a Fundamental Level"). This breakdown also proved to be of great value in assessing the relative merits and significance of different proposed projects; for putting research programmes into perspective in relation

to other work, such as that of the Flame Research Foundation; and for explaining to research students and others what was wanted from them, or being done by others, and why.

It will be seen in the breakdown of Figure 1 that all the elements of the problem considered or examined in partial isolation at some time in the past are introduced at one stage or another. It also becomes self-evident that research at any one individual level can be in itself almost valueless unless parallel work at all other levels is also in progress: the work at the more fundamental levels is required for interpretation and understanding of the results; and that at the more complex levels is required for valid and accurate extrapolation to industrial application. (In passing we may note that it all comes under the heading of applied research though part is, of course, also fundamental). It also becomes clear from this just how difficult (or impossible) it is to extrapolate reliably from, say, the single particle studies to the full scale industrial system in one step, as was occasionally tried in some of the early work; this was another reason for the partial disrepute of fundamental research amongst the development engineers. In fact, building up knowledge for the extrapolation to the more complex systems requires, as the diagram shows, the introduction of only one new element at a time; even the jump from the single coal particle to the single jet flame is too much for one single step. All these general points also apply with equal force in the explosion field.

The Dust Explosion System

Strategy - If we now consider applying these principles to the problem of dust explosions the first step is a strategic breakdown on similar lines to that illustrated in Figure 1. The explosion system is, of course, rather more involved than that of P.F. combustion: as there are many more dusts involved these are additional complications because of their different possible modes of reaction; the conditions under which flames may be expected to occur are much wider; and finally, because explosion flames are unwanted, the practical objective is to prevent or stop them - the inverse of the P.F. requirements.

We may in fact define two practical objectives:

(1) to devise means of preventing or quenching flames; and

(2) to provide information on which to base safety codes and regulations.

The scientific objectives, however, again center round the reaction mechanism, as in the P.F. system, and the suggested breakdown is shown in Figure 2. The close parallel with Figure 1 is self-evident so far as the scientific components are concerned: the coal constitution is replaced by the more general Fuel Types; but in addition, another element has also to be introduced concerned with the physical behaviour of dust deposits and dust clouds - this is a major study in its own right.

The potential complication introduced to the kinetic studies by the different fuels is considerable. At normal temperatures all dusts are solids by definition, but at flame temperatures they can be present as, and react in, the following phases: (1) as solids; (2) as liquids; (3) as gases or vapours; or (4) by reacting consecutively or simultaneously in any two, or even all three, of those three phases. Additionally the oxide may be (when cold) a solid instead of a gas, for example, metal dusts: Ca, Al, Mg, Fe, Zn, Ti, U, etc.

Test and Research Requirements - A totally new element in the problem, however, is the need for a complete set of parallel studies at all levels on the inhibition of reaction and suppression of flame: it is not sufficient to find out how the reaction goes; it must then be stopped again. As the effective agents may very well differ according to the phase the dust is reacting in (solid, liquid, or vapour) this emphasises once again the importance of knowing the precise reaction mechanism. Finally, therefore, it will be necessary to devise, or to continue the development of, a set of tests that will determine accurately the following three characteristics, at the very least:

(1) the ignitability of a dust, or its probability of initiating an incident;

(2) the explosibility of the dust, or its potential for doing damage; and

(3) the phase of reaction, that may determine the type of inhibitor required.

It should now be self-evident that to cover such a broad program as that illustrated in Figure 2, the facilities required by any one research establishment or organization are likely to be inadequate. This means immediately that the lack of sufficient balancing or supporting programs will diminish the value of what work is done. Once again a useful illustration is provided by the work of the Flame Research Foundation. Some recent measurements, in the large oil furnace, of carbon formation and burn-out provided data that were tested against, and found to agree with, a kinetic equation developed from laboratory work. Without that laboratory work these data would have represented one more set of figures relating to specific measurements on a specific furnace, with no indication at all whether they could be applied usefully to other systems. In combination with the laboratory work, this situation is transformed: the elements of the results that hold generally can be separated to a useful degree from the elements specific to the test furnace, and the equation can then be used with considerable confidence as the basis for valid extrapolation. In other words, the value of a co-ordinated set of programs is very much more than the mere algebraic sum of its parts.

Proposal

There are, of course, many organizations actually or potentially concerned with dust explosions. Their combined available facilities for research are considerable and must be fully capable of covering all

the necessary research aspects in the necessary detail but, as past progress on an individual basis has been slow, it would seem to be sensible and economic to co-operate in the facilities that do exist.

As a basis for co-operation, one possible solution would be the creation of a directing committee on the lines of the Flame Research Foundation, together with the necessary research facilities operated directly by the committee. This has many advantages, but what is envisaged as more appropriate to this problem is, instead, a programming committee that would be concerned with: defining the research field; outlining the strategy; pinpointing the outstanding problems; and perhaps outlining tactical methods. In addition it would be able to coordinate and advise on the preparation and use of standard sets of coal and/or other dusts for comparative research purposes. It would then be a matter for individual organizations to select those aspects of the overall field they felt most competent to investigate, and it would also be their choice to select the precise tactics they considered most suitable for the problem involved.

Within the limits of reasonable persuasion and mutual agreement the programming committee would then be finally responsible for making sure that no major gaps were left in the overall program. How far such an advisory-directing agency could function effectively is just not known until it has been tried, but quite obviously its effectiveness would be immeasurably increased if it possessed funds with which it could sponsor research projects, particularly for projects outside the separately-funded research bureaus and establishments. It is suggested therefore that one function of this committee would be to locate and administer the necessary finance for sponsored projects, particularly at universities. This it should be able to do far more easily than individual departments by virtue of the prestige it should carry.

In sponsoring projects, the sponsoring committee could reasonably expect to find some previous experience existing somewhere on practically all the detailed aspects of the problems involved, and it would be generally advisable wherever possible to take advantage of that experience. There may be occasions, however, when this might be undesirable because of the technical problems peculiar to dust research. Few materials are quite so difficult to handle, in such a way as to produce meaningful and interpretable research results, as are dusts. The failure to realize this seems to have been responsible for an immense amount of wasted work, particularly at universities. From discussions with a few of those involved, and from reading the literature, the impression created is that many research projects are started with too little background, and after three or four frustrating years the project director cuts the losses, writes up the little that has been achieved, and turns to something else - just at the point where the experience gained could be used as the basis of a really effective program. Now, in sponsoring projects the committee might well find that such a previous background militates too strongly against interest for success to be possible. However, in sponsoring projects elsewhere exactly the same result can be anticipated unless the committee makes use of its contacts to provide training in the appropriate dust handling techniques for those carrying out the work. This might mean advising on an experimental design, and arranging then for effective supervision

of its construction and commissioning to remove teething troubles. This could mean either the seconding of the operator concerned to an established dust research organization for a month or two, or for the detachment of a competent technician or experimentalist to work with and advise the operator (who may perhaps be a university research student). This could easily save as much as 2 or 3 years that might otherwise be wasted merely in trying to develop a working technique. This suggests that the heading "available facilities" should include previous experience in addition to hardware.

Conclusion

This possibility of pooling experience, techniques, and perhaps equipment is one of the reasons for believing that co-ordinated research could well have a really dramatic impact on the future development of knowledge in this field.

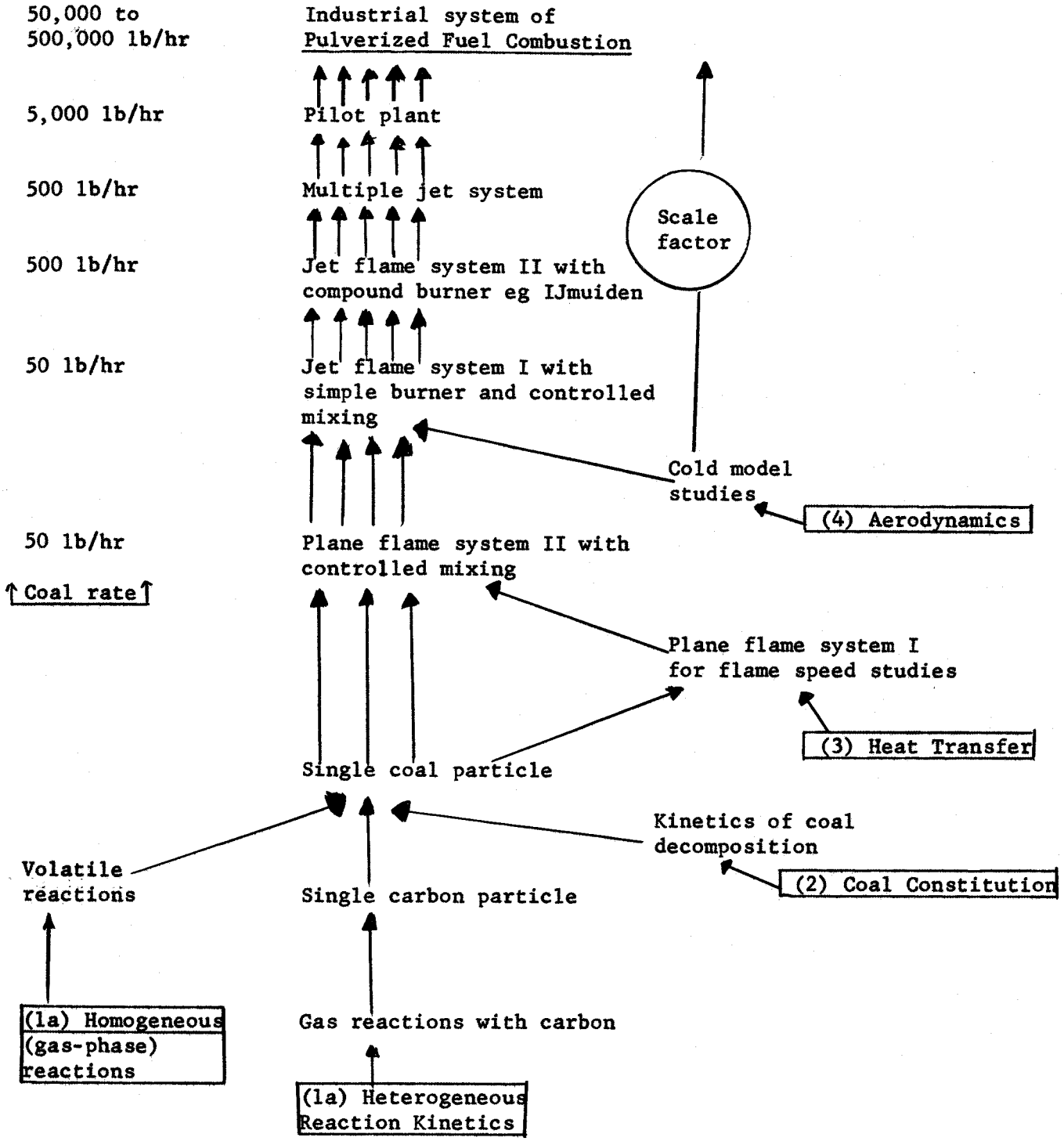

Figure 1 - Schematic breakdown of general pulverized fuel problem.

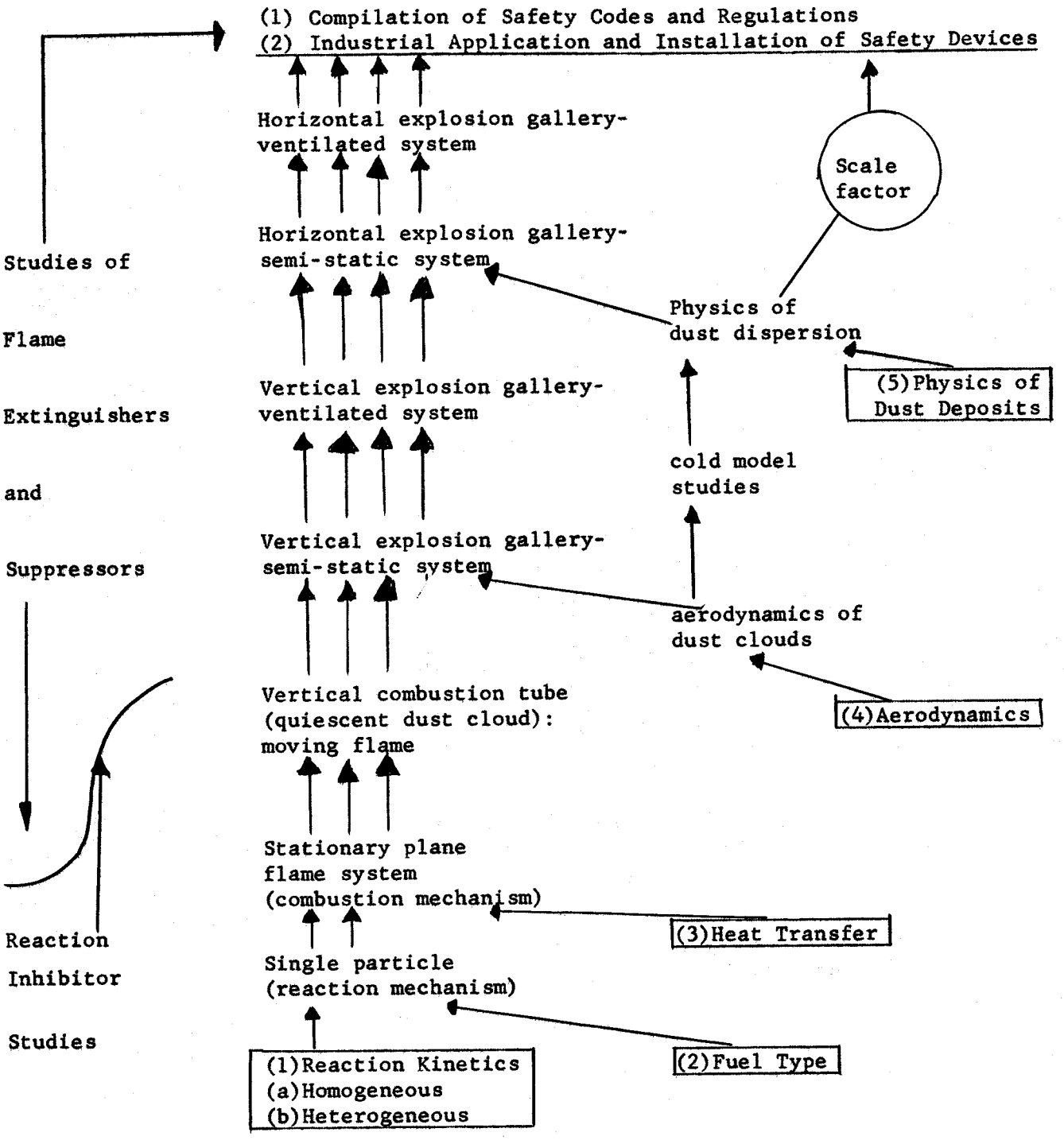

Figure 2 - Schematic breakdown of general dust explosion problem.

Paper 2: Opening Survey
"PIONEERING IN THE STUDY OF DUST EXPLOSIONS"

by

Dr. Hylton R. Brown
Formerly: Chairman; Committee on Dust Explosion Hazards
N. F. P. A.

Introduction

Forty-five years ago a series of tests to determine possible causes of dust explosions were being completed at the Pennsylvania State College only a short distance from the building in which this meeting is being held. These tests centered around the operation of an attrition mill producing different types of grain dust and the investigation touched on various phases of the subject, including sparks produced by foreign material entering the mill, static electricity in the mill, the effect of humidity, and some explosion preventive measures that were suggested during the progress of the work.

The last experiment in this series was conducted on October 3, 1917, and a description of the experiments with the results of the tests were published in a bulletin entitled "Grain Dust Explosions" dated May 18, 1918. This was a joint publication and is designated U. S. Department of Agriculture Bulletin No. 681 and Bulletin 26 of the Engineering Experiment Station of the Pennsylvania State College. The first sentence in this bulletin could well be used as the key-note of this meeting. It reads as follows:

> "The great loss of life and property resulting from explosions in coal mines, flour and feed mills, grain elevators, thrashing separators, etc., emphasizes the fact that carbonaceous dusts are very inflammable and that careful laboratory and field investigations should be conducted in order to devise means for combating this great danger."

Historical Background

In discussing the background material for any proposed study of dust explosions it is always interesting to note the methods used by different scientists in their approach to a solution of the problem and a little historical material may be helpful.

References to the ignition of coal dust are found in a number of reports covering investigations of explosions in English collieries previous to 1850. In 1844 Faraday had suggested that coal dust suspended in air would propagate an explosion, but many of the early investigators believed that such explosions were simply gas explosions in the presence of dust or that gas liberated when the dust was heated would ignite and explode. Later the theory was advanced that some combinations of gas and dust formed explosive mixtures that could be ignited under certain conditions.

About 1875 William Galloway who had served as a government inspector in Scotland and had been in charge of mines in Wales started a series of experiments with coal dust. For this work he used a long box or miniature gallery, and he reported the results of some of this work before the Royal Society in 1876. However, as late as 1880 Galloway testified that it was necessary to have a slight amount of gas present to explode coal dust. Many years passed before there was general acceptance of the claim that coal dust was explosive without the presence of some combustible gas.

Attention was also directed during this period to the hazard of other kinds of carbonaceous dusts. Explosions in flour mills, breweries and other plants handling grain or grain products had occurred. Explosions of this type were reported in the United States as early as 1860 and there are references in the literature to much earlier losses in Europe. Investigators of such occurrences apparently depreciated the possibility of explosive combinations of gas and dust and conducted their experiments with dust alone.

Dust Explosion Demonstrations

Professors Peck and Peckham of Minneapolis are credited with giving the first public demonstration of the explosibility of dust without the presence of gas. In 1878, an explosion at the Washburn Flour Mill in Minneapolis caused the loss of 18 lives, and at the hearings held in connection with the investigation of the explosion, these early investigators demonstrated the explosibility of flour dust by blowing a quantity onto the flame of a candle placed in a wooden box. The cover of the box, on which two men were standing was lifted by the resulting explosion.

The first concerted work on dust-explosion prevention in the United States was undertaken in 1908, when Congress made available to the United States Geological Survey an appropriation for the investigation of mine explosions. A testing station was opened at Pittsburgh in December 1908, and the first public demonstrations to show the explosibility of coal dust without the presence of gas were given in 1908-09. In 1910, the work was transferred to the Bureau of Mines, and work on the subject has been carried on at the Pittsburgh station of the Bureau since that date.

Early Publications

In the years that followed the early experiments and demonstrations there were many reports on dust explosions in different industries and numerous articles appeared in the literature citing personal experience or individual beliefs concerning explosions, their cause and methods of prevention. There was, however, a paucity of scientific treatises based on technical research.

In the United States, in addition to the early bulletins and other publications of the Bureau of Mines there is available a book "Dust Explosions" by Price and Brown, published in 1922 by the National Fire Protection Association of Boston. This book was later translated and

published in Germany. Edwards and Leinbach tested and classified 133 different dusts principally of agricultural origin. In their report of this work in U. S. Department of Agriculture Technical Bulletin 490, the relative inflammability of different dusts is indicated on the basis of pressure produced.

In England, Professor R. V. Wheeler directed extensive research on dust explosions and the results of this work were published in the form of reports from H. M. Stationery Office. Dr. William E. Gibbs, of Liverpool, compiled a considerable amount of data from contemporary writers in 1925 and published it in a book entitled, "The Dust Hazard in Industries."

Dr. Beyersdorfer, in Germany, carried on extensive research on the explosive properties of dust and published his findings in technical and trade journals and a book entitled "Staub Explosionen."

Taffanel published reports of some of his investigations in France as early as 1911.

Bibliographies will in most cases give the modern scientist a clue to the location of data on different phases of the dust explosion problem, but many of the early publications are out of print and available only in certain libraries. Perhaps it would be desirable to plan a volume of abstracts that would make readily available the principal data contained in these early publications.

Early Research

As dust explosion losses of both life and property increased and more dust producing industries developed, the seriousness and extent of the hazard became apparent and research was undertaken by individuals, industrial laboratories, insurance companies and government organizations both in this country and abroad. American, British, French, Dutch and German investigators collaborated to some extent in this work, but without extensive overall planning there was a considerable amount of duplication of effort, variation in testing methods, and differences in recording observations, measurements or other data.

At present the best information on the early research seems to be scattered in a number of bulletins and technical journal articles in this country and abroad. Although proper coordination or evaluation of the early research work is sometimes difficult there is much of value in these early reports that should not be overlooked in planning more advanced research.

Testing Apparatus

The development of testing apparatus is an interesting side light on any dust explosion project. In some of the joint research work conducted by England and the United States, Messrs. Godbert and Greenwald developed a furnace to determine the temperature at which certain dust clouds could be ignited and this apparatus with certain modifications

is being used today. A piece of equipment known as the Clement - Frazer apparatus used in early experiments in the Bureau of Mines to determine the minimum concentration of a dust cloud that could be ignited at a certain temperature consisted of a glass globe having a capacity of one liter with a heated coil at the center to ignite the dust blown into the globe or bomb. It was later improved by adding a gage to record the pressure produced by the explosion. Tests with this apparatus were necessarily restricted to the lower concentrations that would not produce pressures high enough to break the glass globe. Later brass and stainless steel globes were designed for this equipment to permit tests at higher pressures.

A description of other apparatus is given in Bureau of Mines Report of Investigations 5624 "Laboratory Equipment and Test Procedures for Evaluating Explosibility of Dusts," by Dorsett, Jacobson, Nagy and Williams.

The limitations of a small test bomb were recognized by A. H. Nuckolls of the Underwriter's Laboratories who designed a cylindrical metal bomb having a capacity of 20 cubic feet. With this apparatus increased pressures due to variations in concentration and types of ignition could be studied. Underwriter's Laboratories Bulletin of Research No. 30 entitled "A New Type of Bomb for Investigation of Pressures Developed by Dust Explosions" issued in March 1944 describes this equipment and gives the results of tests conducted by Mr. Nuckolls.

The late Dr. Hartmann of the Bureau of Mines determined the explosive characteristics of hundreds of carbonaceous dusts, metallic dusts and powdered materials used in the plastics industry. This work which supplemented the work of Edwards and Leinbach, previously mentioned, was conducted with greatly improved laboratory apparatus as well as ducts, galleries and rooms. The results reported in Bureau of Mines publications is quite comprehensive. This work is being continued by Mr. Nagy and others. One of the most recent publications released this year is Bureau of Mines Report of Investigations 5971 "Explosibility of Dusts used in the Plastics Industry" by Jacobson, Nagy and Cooper which gives data obtained with 313 samples that were studied in the laboratory.

Unusual Sources of Ignition

Following the demonstrations that showed conclusively that dust clouds could be ignited by open flames, attention was directed to some of the more unusual possible sources of ignition. Electrical ignitions of dust clouds were studied by a number of investigators. As early as 1921 Price and Brown reported in U. S. Department of Agriculture Circular 171 "A Recently Developed Dust Explosion and Fire Hazard," the results of tests conducted in cooperation with electric lamp manufacturers. These tests showed that ignitions could be obtained by breaking either vacuum or gas filled lamps in dust clouds and that accumulations of dust on unprotected lamps constituted a fire hazard.

Ignition of dust clouds by static electricity formed on belts and other industrial equipment has been studied in this country by a number of investigators and W. A. Rudge in London contributed some very

interesting data in 1912 and 1913 on the electrification of dust clouds. A self initiated explosion due to the discharge of static electricity formed on the particles of a swirling dust cloud within a tank or bin is considered a possibility by some investigators.

Although the tests referred to at the beginning of this discussion did not show conclusively that sparks produced by foreign material entering an attrition mill can cause a dust explosion, it would be hard to find a scientist today who would deny the possibility of ignitions due to metallic sparks. One of the outstanding contributions on this phase of the problem is the publication by the National Research Council of Canada of the report on "Investigation of the Ignition of Grain Dust Clouds by Mechanical Sparks" by A. W. Morse.

Prevention and Protection

Research work on dust explosion prevention and protection seems to have centered around four possible solutions of the problem, (1) preventing the formation of dust clouds, (2) eliminating sources of ignition, (3) inerting the dust and air mixture, and (4) releasing explosion pressure through vents before damage to equipment or buildings can occur.

The background material on these factors is too voluminous to describe in detail. Many different types of dust collecting equipment are available, but most of them are designed to collect and dispose of undesirable dust particles. Too often the explosive dust or powder is the product being manufactured or handled and there seems to be no practical way to keep such material above or below the explosive concentration during normal grinding, screening or processing.

Considerable progress has been made in eliminating sources of ignition. Safe lighting and heating devices have been developed. Grounding systems are available for the control of static electricity on equipment but the removal of electrical charges from the dust particles themselves is still a problem.

Data are available on the oxygen reduction necessary to create inert atmospheres in enclosures where certain explosive dust clouds may be present, but it is not always practical to use this method of protection. Some dusts require little or no oxygen for combustion and inert atmospheres cannot be maintained in many working areas.

Venting for the release of explosion pressure has been found to be an effective method of protection in many cases. Some information is available on the required ratio of vent area to volume of the enclosure to be protected, and some tests have been made to determine the effectiveness of different types of vent closures. However, determining the proper location of vents has presented many unsolved problems.

Conclusion

Some of the problems mentioned may already be included in the program of research organizations, but many scientists and investigators

are hopeful that through overall planning, effective cooperation and greater coordination more rapid progress can be made in combating the danger of dust explosions.

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Paper 3: THE DUST-EXPLOSION PROBLEM

by

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and

John Nagy, Chief, Branch of Dust Explosions, Health and Safety Research and Testing Center, Bureau of Mines, Pittsburgh, Pa.

Introduction

A potential dust-explosion hazard exists whenever combustible dusts accumulate, are handled or are processed. Our expanding industrialization, combined with development of new products, increases the variety and quantity of materials used in dust form as well as the potential sources of ignition. A major factor effective in the past for limiting the dust hazard is application of knowledge on causes and preventive means gained through experience and research. Through group effort, information can be acquired at a greater rate and disseminated more readily.

Extent of the Dust-Explosion Hazard

Although the problem is worldwide as is evidencedby the considerable amount of research in progress, the following information on the number of explosions, fatalities, and financial loss are presented for the United States. Figure 1 (lower graph) shows the number of major industrial dust explosions, fatalities, and the property loss during the years 1900 to 1960. The data,[1/] are presented by 5-year periods to indicate trends rather than variations in single years. The number of explosions ranges from 25 to 140 per 5-year period, with an average of about 20 per year during the past 30 years. The number of fatalities averages about 10, and the property loss is approximately $2 million per year. The upper graph of Figure 1 shows that the gross national product expressed in constant (1929) dollars has increased from $40 billion to $250 billion from 1900 to 1960. By comparing the lower and upper graphs, it is evident that the number of explosions, fatalities, and cost of dust explosions have not increased proportionately with increased productivity.

Figure 2 presents a further breakdown of the data and shows that during recent years about 1 fatality occurs for each 2 major explosions; the monetary loss per explosion appears to vary randomly; the average is

[1/] National Fire Protection Association, Report of Important Dust Explosions: 1957, 79 pp. (Recent data were obtained by request from the NFPA.)

Work on manuscript completed August 1962.

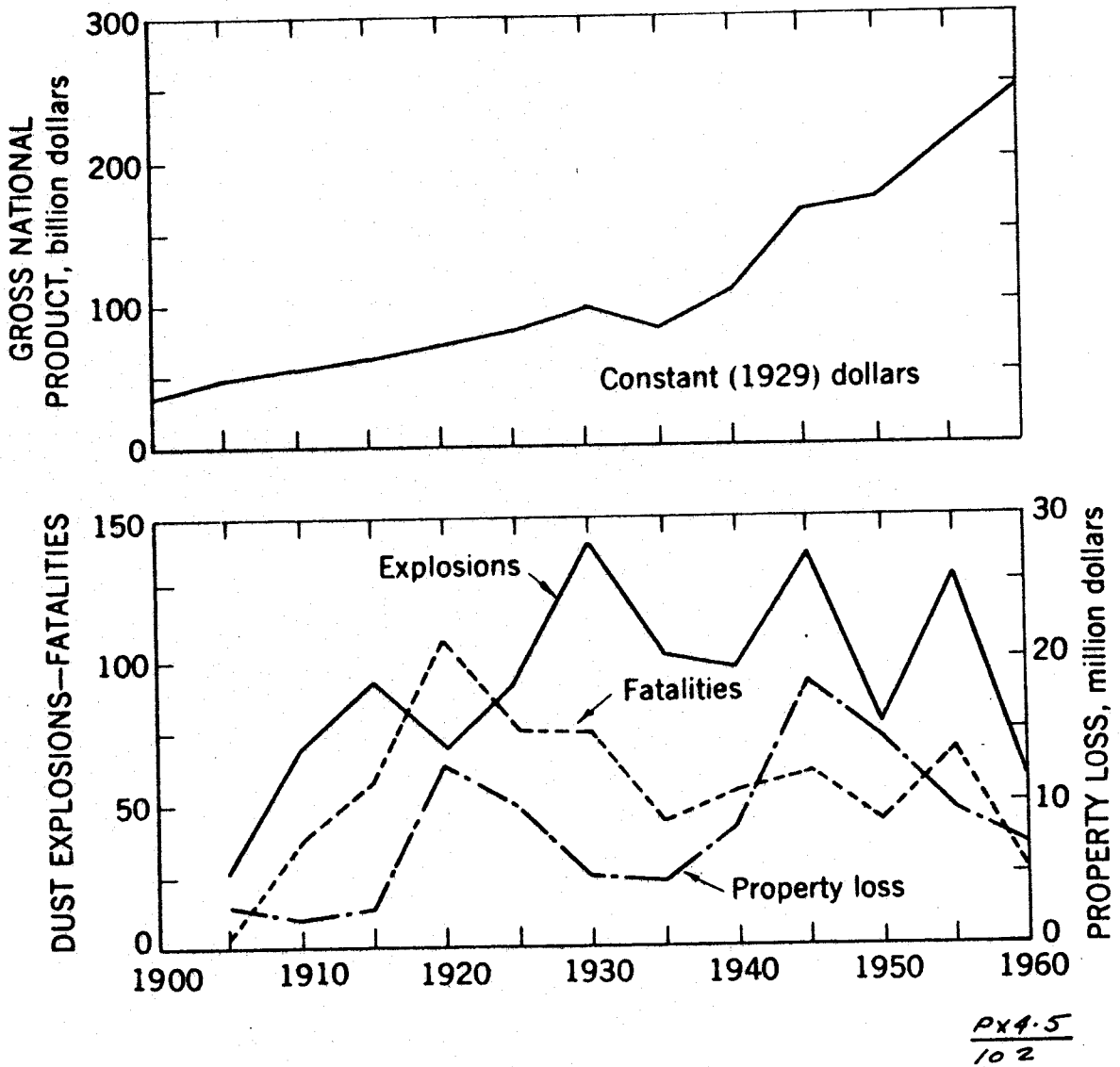


Fig. 1. - Gross national product, dust explosions, fatalities and property loss in the United States by five-year periods.

(Explosion data published by NFPA)

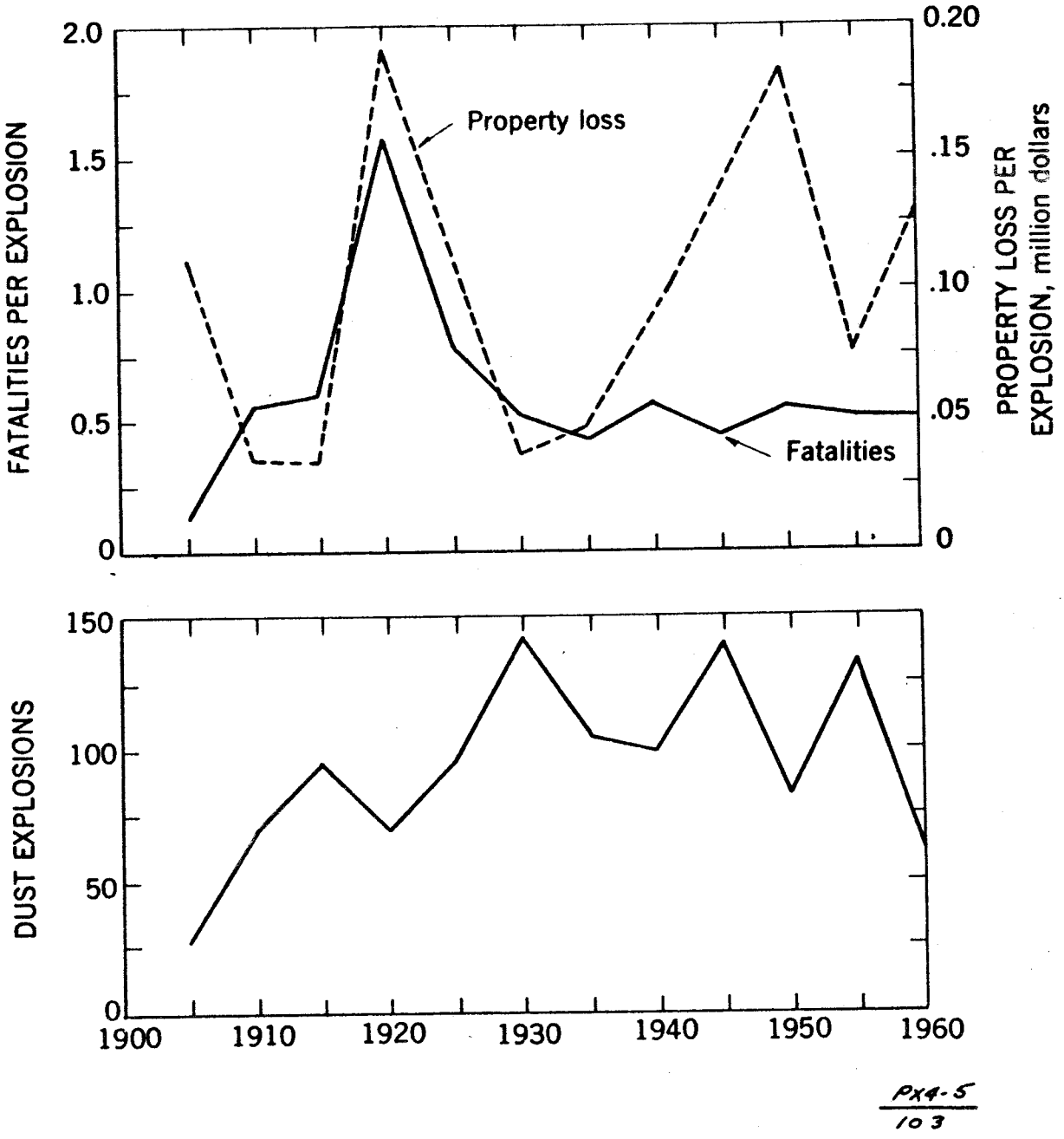


Fig. 2. - Fatalities and property loss per explosion and number of dust explosions in the United States by five-year periods.

(Explosion data published by NFPA)

about $100,000 per explosion. Some minor dust ignitions or explosions in industry are not reported to the NFPA; therefore, the data shown in Figures 1 and 2 are conservative.

One type of explosion not included in the NFPA data are those occurring in furnaces. According to information from Babcock and Wilcox[1/], 156 furnace explosions occurred in 5 years from 1956 to 1960. About one-third of these involved dusts[2/]. It has been estimated that the average cost per furnace explosion is presently about $1 million [3/].

Data for the coal-mining industry are given in Figure 3. The number of fatalities resulting from explosion disasters is gradually decreasing from a high of 475 per year in the 1905-10 period to about 30 at present. Part of this reduction is due to decrease in man-exposure, but the main part is due to education and application of proved safety measures.

In summation, it is estimated that currently in the United States about 35 major dust explosions occur each year causing 40 fatalities at a direct cost of $15 million.

Current Research on Explosiveness of Dusts

In the United States more than 25 major laboratories are engaged in the study of combustion or explosion of dusts; many smaller institutions and companies study related subjects. Active in research on dusts are universities, private research laboratories, corporations, insurance associations, and Government agencies. Perhaps the work of the Bureau of Mines is more familiar to those in industry as this Federal agency has attempted in the past to provide specific information directly applicable to the problems as they arose. However, review of the literature indicates that much fundamental information is developed by other sources.

The investigation of coal-dust explosions has been a continuing activity of the Bureau of Mines since 1910, and it has contributed materially to the knowledge of, and literature on, the causes and prevention of coal-dust explosions in mines, and in industry. A gradual expansion of this work to include all types of mineral, industrial, and agricultural dusts now makes this agency one of the leading organizations engaged in dust explosion work in this country. A limited amount of basic research has been carried forward with a primary interest in the ignition characteristics of various dust particles and on the effects of variables such as radiation on the heat transferred during combustion. In all of its work the Bureau has worked

[1/] Kessler, G. W., Furnace Explosions: The Babcock and Wilcox Co., Barberton, Ohio, 1961, 15 pp.

[2/] Hamming, K. W., Hindenlang, A. W., Livingston, W.L., and Lundberg, R. M., Review of Furnace Protection Design Principles: Paper No. 61-WA-292, ASME, Oct. 1961, 8 pp.

[3/] Smith, J. B., Boiler Furnace Fuel Explosion Survey: Paper No. 59-A-303, ASME, Oct. 1959, 4 pp.

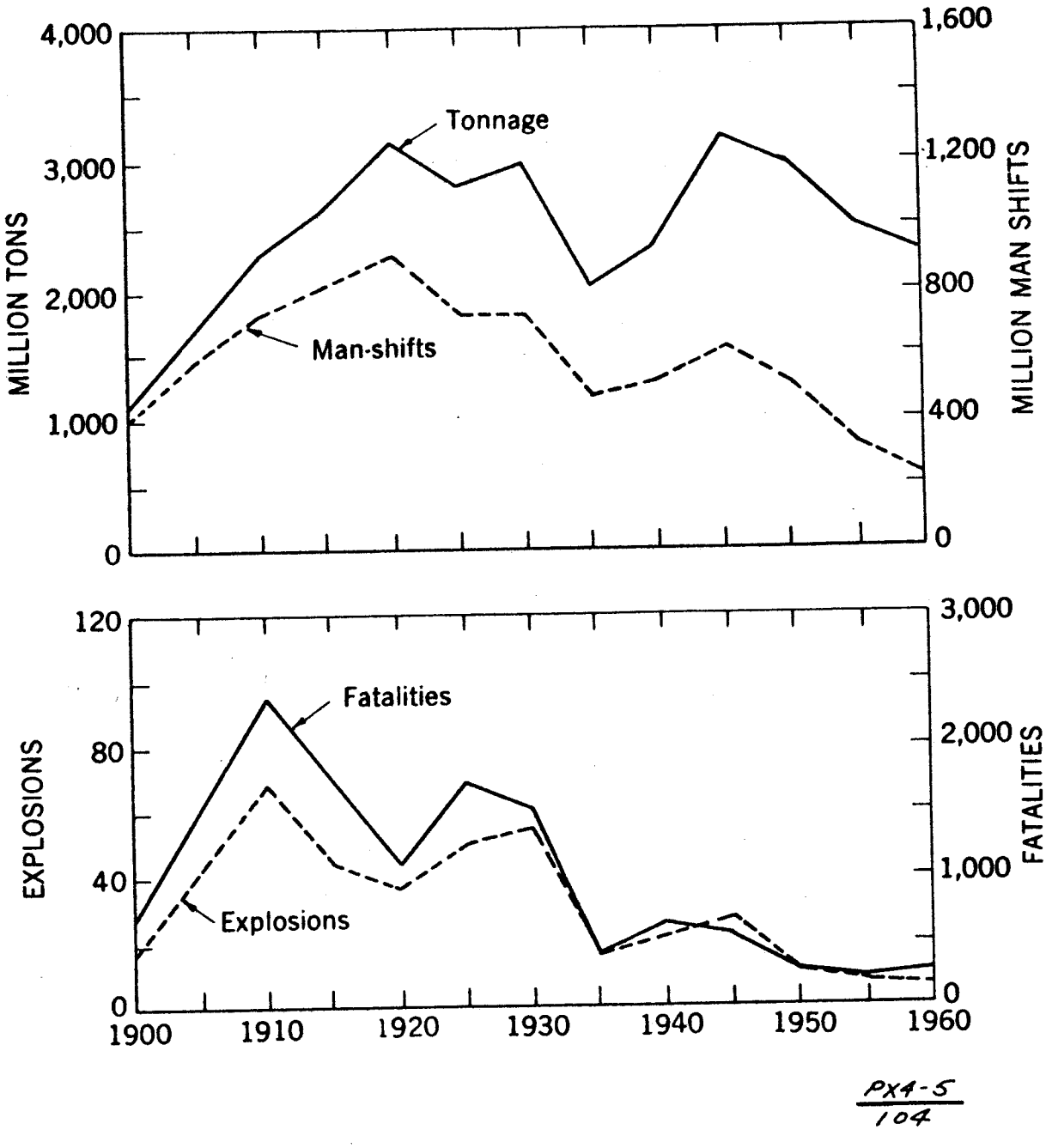


Fig. 3. - Tonnage, man-shifts, explosions and resulting fatalities in coal mines of the United States by five-year periods.

closely with industry in an attempt to provide maximum assistance to solve specific problems. At present emphasis is being placed on investigation of factors affecting the initiation and propagation of explosions; reducing the violence of the explosion should it take place; and the study of hybrid mixtures of combustible dust, flammable gas and air, such as exist in many mining and industrial operations. The results of the Bureau's investigations on dust explosions are available to the public through the various Bureau of Mines publications, and through presentation of scientific papers at technical meetings, and publication in technical journals.

As mentioned previously, there are a number of laboratories in this country engaged in research applicable to dust explosion suppression. Much of this research is performed to solve specific industrial explosion problems such as are encountered in furnaces, coal dryers, and plants producing metal dusts, plastics, etc. In some cases the results of the research are never published and the work is lost to the literature in the field. Every effort should be made to obtain the widest possible distribution for all information pertaining to dust explosions.

Major research programs have been in operation for years in a number of countries. The excellent research of the British on the hazards of dust explosions is well recognized. The work of the Safety in Mines Research Establishment has been particularly outstanding. The work of the Germans in dust explosion research is noteworthy; they are perhaps the only country with a publication (STAUB) devoted exclusively to dust problems. The Dutch, French, Italian, Japanese, Polish, and Russians among others, have conducted research on dust explosions for many years.

Discussion

Although dust explosions account for but a small proportion of the losses sustained from uncontrolled fires and explosions, the loss of life and property from this source cannot be disregarded. We hope that this meeting will serve to point out some of the more important needs and thus stimulate renewed interest on the part of research workers and organizations dealing with combustion and dust-explosion technology.

In its policy of promoting safety in American industry, the Bureau of Mines considers that an organized effort will be more effective in reducing the frequency and severity of accidents caused by dust explosions. Coordination of research on phases of ignition, combustion and explosion of dusts is desirable. Research efforts need to be increased and the information so obtained should be more widely disseminated. Organizations such as the NFPA and ASME should be given assistance in preparing instructions for safe operating practices.

Although acceleration of research on the causes and prevention of dust explosions is most necessary, the desired measure of success will not be achieved without the full cooperation and interest of those in industry responsible for the application of the principles developed.

Paper 4: DUST EXPLOSIONS

by

P. Laffitte and R. Delbourgo
University of Paris, Paris, France

I first want to thank the chairman and organizers of this conference on Dust Explosions Research for having thought to contact us when this meeting was being prepared and decided. When Dr. Essenhigh wrote to us in Paris to invite us to attend this meeting, our first thought was to decline the invitation on the very sound grounds that neither of us, Professor Laffittee nor myself, were specialists of these questions which are much more the concern of the CERCHAR (French coal board research center). However, since we were visiting this country on the occasion of the IXth Symposium on Combustion, we thought we could take advantage of this opportunity and accept Dr. Essenhigh's invitation to this conference more as observers than as contributors.

In putting us down on the program as speakers on "Facts and Figures", Dr. Essenhigh has not only overestimated our contribution to this point but has also slightly misled the audience who may in the whole be disappointed to hear how little facts or figures we are going to report on the situation in France.

Before leaving France we endeavored to assemble some information on accidents and explosions having occurred in that country in the last few years and that could be actually pinpointed to a dust explosion cause. This information was obtained through the cooperation of the ANRT (French National Association for Technical Research) and the CERCHAR to whom we are grateful.

As far as coal mines and coal dust explosions are concerned this information is in the hands of the CERCHAR. To the best of our information, there has only been in France one or two major dust explosions in coal mines in the past ten years leading to some casualties and important financial loss. In each of these cases it has been extremely difficult to assess the part played in the explosion by the explosive dust and that due to firedamp. In most cases these two factors are intimately interconnected.

As we all know, a potential explosion hazard not only exists with coal dusts but also with many other combustible particles which are now industrially handled and processed in everyday life. Sugar and flour industry are two examples amongst others. In the flour industry, for instance, a few minor accidents have occurred and have been reported in the last few years, the causes of which have in most cases been attributed to static electricity. In this juncture the relative humidity ratio seems to play an important role and an optimum humidity content appears to be necessary to reduce this explosion hazard and its subsequent fire danger. Also, geometrical factors introducing or reducing turbulence have been studied with some interest.

As far as our personal contribution to dust research is concerned, I will say that we have approached the matter in a roundabout way since

our work concerns primarily not so much the explosion of combustible dusts but the influence of dusts on inhibiting explosions.

These two apparently entirely different fields of research have, however, in common a certain number of points. In particular, some of the techniques and apparatus involved can be very similar since a dust explosion is studied in both cases. Recently, we have developed a technique suitable for the introduction of a dust sample into a tube filled with a gaseous mixture and this technique could eventually be used for the study of a combustible powder in air or in any atmosphere.

A paper on this technique and the results obtained was presented last fall at the ACS meeting in Chicago and has just been published in Fire Research and Abstracts Reviews. Perhaps I could show one or two slides on the device itself without going much into details.

The apparatus consists of a vertical pyrex tube 2.50 cm. in diameter and 2 m. long. The slide valve near the top of the tube is made of a very thin (0.2 mm.) berrylium bronze blade working like a camera slide shutter. This is vacuum tight through the use of 0 rings. It can be triggered open either mechanically or pneumatically and the aperature can be synchronized with the ignition device - electric spark, heated coil, or detonating cap - at the bottom of the tube. If a given sample of dust is set on the blade, the sudden opening of the shutter sets the powder falling. If a relay is placed between the opening of the slide and the ignition device, then the powder is free to disperse along the tube a convenient distance before ignition occurs.

This apparatus has been used with some success and has proved to give extremely reproducible results. It could in our opinion be extended to the study of combustible dusts as well as the addition of a dust to combustible gaseous mixtures, which has been our present concern.

This in fact brings me to the next point I want to raise on these questions; this concerns the test and research requirements in these dust problems. We feel it imperative that a fundamental approach to these questions be considered, and that a number of methods be developed to standardize the systematic study of dusts. This should include not only explosive dusts, but also, in later steps of research projects, the study of the influence of small proportions of various solid inhibitors on the combustion and inflammability of combustible dusts. This latter, of course, is primarily of concern in coal dust problems, and is not likely to be of interest for food: eg., sugar and flour. Of course, I am fully aware of the difficulties pertaining to the combustion of solid particles at a time when homogeneous reactions are far from being fully understood. It is, however, our opinion that a stimulating field of research lies ahead and that little fundamental work has actually been done to this day on this subject.

In conclusion, I will come back to "Facts and Figures" to say that if, after all, the picture I have given you of the fatalities and financial losses in our country is very low, I feel we can only be very happy about it. But this should not make us too happy and forget that there seems to be a definite need for centralized information; moreover, there

is need for a basic approach to these problems through the development of valid research methods together with the systematic application of these methods to different inflammable dusts even though these may well behave quite differently because of their particular chemical composition and physical structure with respect to such parameters as, for instance, particle size or humidity content.

Thank you.

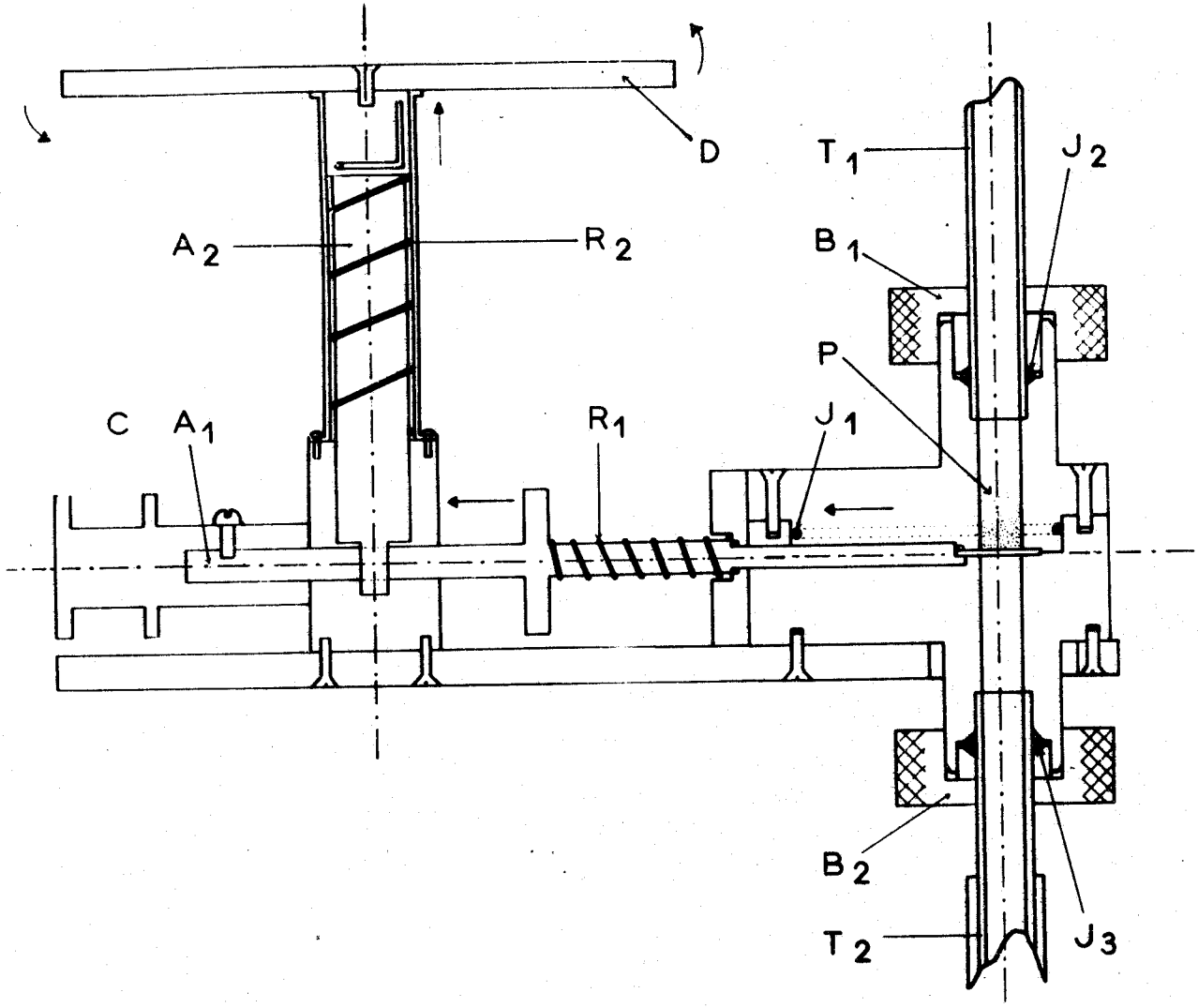


FIGURE - Slide-valve dust-injector.

Paper 5: "PROPOSALS FOR EXPERIMENTS ON DUST EXPLOSIONS"

by

Robert H. Essenhigh
Associate Professor of Fuel Technology

Introduction

Research on dust explosions has been in progress intermittently for 100 years and continuously for more than 50, but accurate quantitative prediction of explosion behaviour - predicting flame temperatures, speeds, combustion limits, pressures, etc: - is still not possible. This is not so much a consequence of failure of research as of inadequate and/or limited-objective research. Initial assessment of the problem underestimated its magnitude * and, in addition, much of the research effort was inevitably directed, for reasons of urgency, towards ad hoc studies of prevention and suppression. The fragmentary and largely empirical nature of the work so far carried out has made correlation and collation of the work very difficult, and in many cases impossible; but the wide practical knowledge that we now have, even though largely empirical, now gives us a sound basis for designing crucial experiments designed to test theories rather than continue the mere accumulation of unrelated and often unrelatable "facts." The proposals set out in this paper are based in general on the writers previously circulated paper "Dust Explosion Research: An Appraisal"; but, specific proposals for experiments are based on - and designed to test - the assumptions and predictions of the analysis contained in the paper "Combustion Phenomena in Coal Dusts" /Colliery Engineering 38 (1961) 534; 39 (1962) 23, 65, 103./

Subject Breakdown

The schematic breakdown of the general dust explosion problem is illustrated diagrammatically in Figure 2 of the "Appraisal"; the subject breakdown given here (below) is based on that schematic breakdown and is intended to provide subject headings for subsequent amplification into explicit proposals for experiments.

Group 1: Dust Behaviour

1.1 Static - tests on small beds
1.2 Dynamic - 1.2.1 motion of dust clouds (steady state)
1.2.2 dispersion of dust clouds (transient state)

*For Example:

The British Coal Dusts Experiments Committee (forerunner of Safety in Mines Research Establishment) who started work at Altofts in May 1908, chose a circular gallery constructed of boiler shells in preference to a rectangular gallery since "on completion of the tests there would have been no sale for the plates . . . (but) . . . there is usually a sale for second hand boiler shells" (!) /Altofts, B.C.D. Experiments Report: The Colliery Guardian Co. Ltd.; London; (1910) p. 10./

Group 2: Combustion Mechanism and Flame Propagation

2.1 Single particles
2.2 Stationary (plane) flames
2.3 Moving flames in quiescent dust clouds
2.4 Explosion flames in vertical galleries
2.5 Explosion flames in horizontal galleries

Group 3: Flame Suppression

3.1 Reaction inhibitors
3.2 Thermal flame suppressors (thermal loading by stonedust and water)
3.3 Velocity extinction
3.4 Pressure release panels

Group 4: Gallery Behaviour

4.1 Dispersion tests - Validation of gallery dispersion equation.

4.1.1 on stonedust
4.1.2 on coaldust
4.1.3 on mixtures

4.2 Combustion tests - Validation of gallery extinction equation.

4.2.1 Validation of extinction equation
4.2.2 Determination of extinction limit parameters

Notes on Subjects

The purpose of this section is to amplify the subject headings and to outline some of the factors that are either believed or are known to affect the subject under consideration. This also indicates in some instances the type of experiment or experimental method that would probably be suitable to get the information required.

Group 1: Dust Behaviour

1.1 Static - Elucidation of physical properties of dust packings by studies in the style of classical physics of the causal relationships between porosity, permeability, particle size, particle-size distribution, cohesion, repose angle, bulk density, moisture percentage, etc. At present the bulk of the available data, with the chief exception of permeability studies, is of a predominantly statistical nature. Experimental studies have now shown that statistical correlation between the parameters listed above is generally significant. This, of course, could reasonably have been assumed at the start of those studies; what is now required is elucidation of the causal relationships.

1.2 Dynamic - The behaviour of dust clouds, and the mechanism of the dispersion of dust deposits into clouds, have both been quite extensively studied, as a recent B.C.U.R.A. Monthly Bulletin Review

has fully brought out; but this Review also brings out just how inadequate and unsatisfactory is the theoretical understanding of these joint phenomena. Theoretically there has been little real advance on Einstein's (1905) equation for the increased viscosity of a particle-bearing fluid; and concerning relative motion between particles and fluid in dense concentrations, it does not seem to be generally known that the Stokes, Allen, and Newton equations are inadequate to inapplicable. On dispersion, there are quite a lot of data and many theories, but no reasonably developed predictive analysis yet exists that has been or can be tested against appropriately designed experiments.

Group 2: Combustion Mechanism and Flame Propagation

The objective in this group or experiments is a full theoretical understanding of the behaviour of an explosion flame in a horizontal test gallery (using either preformed dust clouds or *in situ* generated clouds). The series of proposed experiments leading up to this is through (i) the single particle; (ii) the stationary (plane) flame; (iii) the moving flame in a quiescent cloud; (iv) and the explosion flame in a vertical explosion gallery. In this proposed build-up, much has already been accomplished by way of theoretical analysis and development of appropriate experimental techniques - too much to summarize here - but what has had least attention, except on an *ad hoc* basis, is flame behaviour in the horizontal gallery. The experimental systems proposed for study are horizontal galleries, of glass (Pyrex) where possible, of dimensions up to 6" or 8" diameter and 10' to 20' long. The objective would be to study explosive propagation flames, with and without ventilation currents, with a view to:

(a) determination of explosion limits by: (1) oxygen enrichment and vitiation; (2) inert dust; (3) as a function of precombustion ambient temperature; (4) as a function of coal rank and fineness; (5) as a function of added methane or firedamp;

(b) study of flame speeds and burning velocities relative to both the containing tube and the moving cloud, and elucidation of the combustion mechanism as functions of the above mentioned parameters.

Group 3: Flame Suppression

Means of preventing flame, or to suppress it after it has been initiated, are a most important but somewhat heterogeneous collection of materials, devices or operations. Materials that interfere with the chemical reaction are reaction inhibitors; and those that act physically by thermal loading to an upper limit, or by dilution to a lower limit, are termed suppressors. Propagation is also known to be sensitive to the ventilation current in the pre-explosion system - above certain velocity limits the flame fails to propagate, but why is not known. The opposite effect is produced by explosion relief panels that are blown out by the pressure of the passing flame; the cloud expansion permitted reduces the velocity of the moving cloud in the explosion duct, and as the dust falls out of suspension the flame is killed. In past studies of these systems, much has

already been done, even though interpretation is still often ambiguous; future studies, however, might well wait on the completion of initial Group 2 experiments since the conditions required for flame extinction and suppression are essentially limiting boundary conditions in the mechanism of ignition, combustion, and flame propagation. Successful completion of experiments in Group 2 should therefore provide, as a by-product, information on how to prevent and suppress flame.

Group 4: Gallery Behaviour

4.1 Dispersion tests - Full understanding of the dispersion mechanism to be obtained from the laboratory experiments, will be necessary for a complete interpretation of gallery dispersion tests; but much of great value can be done in the meantime by validation of the Gallery Dispersion Equation. Using a full scale dispersion gallery, the first objective would be to test the validity of the equation on pure stonedust, pure coal dust, and then on mixtures. If this proved satisfactory, further experiments would be designed to investigate the dependence of the equation dispersion parameters on: dispersing blast intensity; coal and stone dust fineness; cohesion; moisture content, etc. Knowledge of behaviour even at this semi-empirical level would serve two purposes: (i) it would provide sufficient information for adequate interpretation of the explosion tests; and (ii) it would provide a body of empirical knowledge on dispersion behaviour that would provide a predictive objective for the dispersion theory to be developed as part of the Group 1 investigations. In this way, different components of the problem are separated or "decoupled" from each other for independent study.

4.2 Combustion tests - Here again, full interpretation and understanding of the experimental results will be dependent on satisfactory completion of experiments in the other groups; but again much can be done in the meantime, in this instance by validation of the Gallery Extinction Equation. Several sets of experiments can be proposed.

(1) Validation of the extinction equation

(2) Determination of blast intensity from the cannon and impetus tube unit as a function of: coal rank; coal fineness; stonedust type, etc., in the impetus tube (these experiments would also be part of the dispersion tests of Group 4.1 above).

(3) Tests of basic theoretical proposals and assumptions regarding: (i) ignition; (ii) proposed extinction mechanism; (iii) suggested influence of impetus tube (test initially by blast meter, in blank experiments, using only cannon igniter with variations in the impetus tube mixture).

(4) Determination of equation extinction parameters as functions of: (i) dispersing blast intensity; (ii) coal fineness; (iii) coal rank; (iv) stonedust type; (v) firedamp percentage.

(5) Test of decomposition theory by stonedust analysis to check percentage limestone decomposition at impetus tube and throughout explosion gallery.

(6) Test of ignition and propagation proposals by gas analyses throughout gallery to check degree of partial and/or complete combustion.

Conclusion

It is important to emphasize that in most instances the proposed experiments need no longer be carried out on a "suck-it-and-see" basis; sufficient predictive theory now exists, whether right or wrong, for experiments to be designed to test expectations. If the experiments substantiate expectation, well and good; but even if not, the discrepancy between expectation and experiment still can be expected to provide a valuable guide to the real interpretation and behaviour.

Paper 6: Status Report SR 2
Activities of the ISA Subcommittee on Electrical-Dust Hazards

by

Tom W. Moodie
Subcommittee Chairman, Instrument Society of America

The objective of the Instrument Society of America (ISA) is to advance the theory, design, manufacture and use of instruments and controls in science and industry.

One of the departments of this national society is the Standards and Practices Department of which there are many committees. One committee, known as RP12, is responsible for "Safety for Electrical Instrumentation in Hazardous Areas" and has appointment a subcommittee (RP12A) to handle liasion with writers of the National Electric Code. Another subcommittee (RP12B) is responsible for "Safety for Electrical Instrumentation in Dusty Hazardous Areas." A Review Board reviews proposals for the improvement of electrical safety practices.

The stated purpose of the parent committee is "to promote uniform, safe and economical instrumentation for hazardous areas." This purpose is adopted by the dust subcommittee with the insertion of the word "dusty" in the statement.

History of the Parent Committee

On the 6th of November, 1951, members of the American Petroleum Institute concerned with instruments and members of the Chicago area Instrument Society of America met with the late Mr. Parks, then Chairman of the National Fire Protection Association's Panel 14. Mr. R. R. Proctor of Pure Oil Company organized the meeting which was attended by about a hundred people involved and interested in the explosive hazards of gases, vapors and dust. They met at the Western Society of Engineers Building and generally agreed that the National Electric Code had not kept up with advancing technology in such areas as the application of vacuum tubes, general purpose equipment in panels, thermocouples and cables in hazardous areas.

Mr. R. R. Proctor emerged the first chairman of ISA's Standards and Practices Committee, which had fifty members. Their early activities consisted largely of exploring the particular special interests of members.

About two years later, a committee was formed which could restrict the special interest discussions and reach down to the more fundamental issues at hand. The first chairman of this group, Mr. Anderson, of Panellit, Inc., was succeeded by Mr. H. W. Ecker of the Minnesota Mining and Manufacturing Company. Some years later, Mr. Frederick L. Maltby of the Drexelbrook Engineering Company became and remains chairman of this parent committee.

In 1953, over objections of members concerned with dust hazardous areas, the original parent committee decided to limit the scope of the activities to class 1, gas and vapor areas, in order to achieve some definite goals.

This committee has changed members since 1953 because of changes in the responsibilities of members within their own firms, but the goals and mode of operation have remained essentially the same.

On April 11, 1960, the parent committee's recommended practice RP12.1, "Electrical Instruments in Hazardous Areas," was approved for publication by the Standards and Practices Board. It was prepared by eleven members of the parent committee and reviewed by a nineteen member Board of Review. RP12.4, "Instrument Purging for Reduction of Hazardous Area Classification," has likewise been published.

Two very pertinent changes which are in the National Electric Code which were actively sponsored by the parent committee are:

1. 5013b. Liberalization of class 1, division 2 requirements were allowed which permitted a wide range of industrial instruments to be used in division 2 areas with only minor modifications. General requirements are that in normal operating condition instruments must not contain a source of ignition.

2. 5001. Recognition of the principle of intrinsic safety. As another case in point of the recognition of the principle of intrinsic safety, the code now permits in division 2 areas, "slide wire contacts . . . used in conjunction with thermocouples."

The parent committee is diligently finalizing a recommended practice that will be known as RP12.2, Intrinsically Safe and Non-Incendive Electrical Instruments.

One important activity of the parent committee is known as "inform and influence," as described by Mr. Frederick L. Maltby, our parent committee chairman. The committee has shared information that has been accumulated with interested companies and technical groups. The largest single effort was exerted with the Wilmington, Delaware, section May 2 and 3, 1960, when they sponsored a symposium of Safety for Electrical Instrumentation. See ISA Proceedings "1960 Symposium on Safety for Electrical Instrumentation in Hazardous Areas."

Dr. Delbert Olson of Minnesota Mining and Manufacturing Company in St. Paul was asked late in 1959 by the parent committee to appoint a Dust Subcommittee to develop a dust program. On February 5 of 1960 he called together Mr. J. H. Anderson of The International Milling Company, Mr. Warren Carlson of The Corn Products Company in Chicago, Mr. T. W. Moodie of The Pillsbury Company, Mr. G. R. Olson of Archer Daniels Midland Company, and Mr. Alger Ulstrom of General Mills, Inc., now retired but still active on the subcommittee.

All these members were from the Minneapolis area with the exception of Mr. Carlson. Since then, Mr. Vern Johnson of Cargill, Inc., Minneapolis, has been added to the subcommittee. This subcommittee is

now known as number 8D-RP12-B. Mr. Warren E. Carlson, our first chairman, was succeeded by T. W. Moodie on May 24, 1960. Mr. Harold Kuehn now represents General Mills, Inc.

Activities of the Subcommittee

The activities of the subcommittee have centered around attempting to develop a recommended practice that could be applied in the dust hazardous areas. In so doing, we are attempting to reword recommended practices RP12.1, "Electrical Instruments in Hazardous Areas," and RP12.4, "Instrument Purging for Reduction of Hazardous Area Classification."

In the above recommended practice, the parent committee referred to explosive lower limit concentrations of hazardous gases and vapors for which they had techniques and instruments for measuring. Certain construction is described as suitable in atmospheres that are hazardous most of the time. Under emergency conditions, less expensive equipment provides the same degree of protection.

The dust subcommittee, in attempting to prepare similar recommendations for dust hazardous areas, realized that the recommendations would be like hollow shells without the meat of clearer specification for the classification of areas. The area is classified in Class 1, areas based on measurement of concentration and amount of high concentration time. No similar field instrument and method was accepted in the industry for similar analytical work on dusts.

We made ourselves familiar with the American Petroleum Institute's "Classification of Hazardous Areas in Petroleum Refineries," RP500. We wanted by similar methods to classify dusty hazardous areas. Again, we came up to the problem of not being able to measure dust concentrations.

On the advice of Dr. Kenneth Whitby of the University of Minnesota, a spot filter-type sampler was sought out and found. With spot samples, the committee has sought a feel for the scale of the magnitude of concentrations actually found in plants. Previously it was not known how close the operating areas were coming to explosive conditions. This equipment was secured from the Gelman Instrument Company of Chelsea, Michigan.

The spot sampler has many shortcomings which can only in part be overcome by a continuous sampler which could be fitted with a recorder to permit analysis of concentrations at one location over a longer period of time.

There are a number of instruments that are used in "white room" sampling and analysis. There the dirt being collected is of the nature of lint and shop dirt. The places that are manufacturing precision instruments for military and missile work have this type of equipment to use.

Similar equipment is used by public health service authorities for the analysis of air-born contamination. Again the material being

collected is of the lint and dark carbonaceous nature. Some of these instruments work very satisfactorily. In such applications, a photoelectric absorption principle calibrated on a weight basis is used.

In the food manufacturing business, there are explosive dusts that are near white or in many cases of a distinctly colored nature. For this reason the photoelectric principle of sampling requires considerable variations in calibration procedures.

We've sought out an instrument which produces its indication on a weight or mass basis. On the suggestion of Dr. Whitby, we learned that the U.S. Public Health Service in their Taft Research Center in Cincinnati has developed an instrument for field sampling of air-born contamination. See "A Mass Loading and Radio Activity Analyzer for Atmospheric Particulates," Nader and Allen, #59-28, Air Pollution Control Association, Pittsburgh. The "Reports of Investigation" of the Bureau of Mines' Health and Safety Branch, are very useful for understanding of the type of problem and the scale of values involved: RI4725, Recent Studies on the Explosibility of Cornstarch; RI5624, Laboratory Equipment and Test Procedure for Evaluating the Explosibility of Dusts; RI5754, Explosibility of Agricultural Dusts (220 of them.)

Research data on concentration levels and energy levels are available for many pure products. For products whose characteristics are not known, concentrations and energy levels can be determined by the methods of the report of investigation RI 5624, "Laboratory Equipment and Test Procedure for Evaluating the Explosibility of Dusts."

The committee honestly believes it is on the verge of a breakthrough in the area of measurement for the classification of hazardous materials and areas. The principle lack is a suitable continuous recording instrument with a proper range. Without such an instrument, any recommended practice written would be quite sterile. The Public Health Service instrument has a fine unit for its purpose where concentrations are relatively minute. It may be that this instrument can be adapted by proper changes in range to measure concentrations near the lower explosive limit.

The various uses of an instrument capable of measuring dust-air concentrations can be grouped into three categories:

1. Health and Safety. Such a measuring device can aid the design of equipment by determining the types of controls and equipment that can be used in dusty atmospheres, can serve as a high limit control to assure safety and industrial health by either shutting down the process, sounding an alarm, or taking corrective action - - switching on ventilating fans, for example.

2. Engineering. In addition to the engineering design applications intended to protect health and safety, a dust concentration measuring device will have many applications to process control, in mixing and blending operations, in determining the amount of product lost in a process, in optimizing development and providing numerical specification parameters for new equipment, and in locating sources of dust escape.

3. Sanitation. Although sanitation procedures and practices are considered an intergral part of process design in many industries, a dust measuring instrument can aid in the design of plant sanitation procedures to assure compliance with Food and Drug requirements. Plant cleaning frequency rates and cleaning equipment efficiency, for example, can be determined with such an instrument.

Invitations to bid on the specifications describing this recording instrument have been sent out. A number of proposals already have been received. When, in the judgment of the committee, the best instrument has been found, funds, will be needed to purchase a prototype unit. It's expected that subsequent ones will be purchased privately by the benefiting corporations.

It appears that prototype continuous recording samplers of a Mass Loading and Radio Activity type will cost between $6-8 thousand; production models, from $2-5 thousand.

We are sure that industry, insurance and electrical inspectors, and employees are all keenly interested in the question of what degree of hazard actually exists in an area. Until now, there has been little more than accident experience to guide us. Most engineers have a conviction that if they must err they would rather err on the side of safety. At the same time, economic pressures are building to eliminate all unnecessary costs that reduce the return on capital invested in manufacturing facilities.

The committee holds that there should be clearly defined safety factors in any recommended practices that are adopted. New recommended practices should be based on sound scientific knowledge and principles. I believe it was Mr. Weston who was quoted as having said, "We don't really know unless we can measure it." To be sure, sound engineering judgment will be involved in any conclusion for classification of an area. However, the principles involved in the proposed recommended practice will by measurement reduce the possibility of error in a judgment to a great extent.

The classification recommended practice is intended to be a general treatment that will handle both present and future technology. The present National Electric Code has not kept up with modern technology; developments such as solid state logic components, potted components, transistors, and magnetic amplifiers.

The committee has done some publicizing of its activities in communications with the Bureau of Mines, the U. S. Public Health Service, Factory Mutual, The Factory Insurance Association and the American Association of Operative Millers.

To date the activities of the committee have been financed by committee member's companies.

The present purpose of the subcommittee is to provide a sound Recommended Practice which will guide engineers and inspectors in the little understood areas of classification of degree of hazard. If the subcommittee can provide this Recommended Practice, we would like to see it

result in changes in the National Electrical Code, and applied to guide new installations and to appraise hazards in existing facilities.

In order to accomplish this goal, money is needed to buy the prototype instrument and to develop the calibration to the concentration levels established by the Bureau of Mines. With a calibrated instrument, studies will be conducted and a Recommended Practice will result. The next step is to persuade the National Fire Protection Association's Code Panel 14 to adopt the Recommended Practice, including the reclassification of areas.

Firms are represented in various ways on the code making panel: there are representatives on Panel 14 from interested and knowledgeable companies, insurance associations and engineering technical societies. Many of you can influence the improvement of codes through your representation on the code making committees of these authorities.

The projects expected to be concluded by the subcommittee in the future would include investigations into intrinsic safety, purged enclosures, static electricity, and the dust parallels of recommended practices which the parent committee is developing for gas and water vapor areas. Concerted efforts are being made to have a recommended practice for Intrinsically Safe and Non-Incendive Electrical Equipment in areas made hazardous by a cloud or blanket of combustible dust. The dust subcommittee hopes to carry on a parallel activity with the parent committee to provide the dust industry with as up-to-date Recommended Practices as the state of the sciences and the economic need will justify.

It is the belief that where there is now guesswork, fear and overprotection, there can be confidence, knowledge, and economy in the protection of personnel and investment.

APPENDIX 1: List of Registrants

Name	Company	Co. Address
Ault, W. E.	Automatic Sprinkler Corp. of America	P. O. Box 360 Youngstown, Ohio
Blackwell, D. A.	Union Starch & Refining Co., Inc.	19th and R. R. Granite City, Ill.
Blaesi, C. M.	Indiana Lumbermans Mutual Ins. Co.	429 N. Penna. St. Indianapolis, Ind.
Bodurtha, Frank T.	E. I. duPont de Nemours and Co.	Louviers Bldg. Wilmington, Del.
Brown, Hylton R.	Retired	9112 2nd Ave. Silver Spring, Md.
Carlson, Warren E.	ISA-8D-RP12-B	330 E. Franklin Wheaton, Ill.
Coffee, Robert D.	Eastman Kodak Co.	Kodak Park Bldg. 35 Rochester, N. Y.
Cole, Frank J., Jr.	Eastern Gas and Fuel Associates	250 Stuart St. Boston 16, Mass.
Crouch, Harold W.	Eastman Kodak Co.	Kodak Park Bldg. 35 Rochester, N. Y.
DeCoudres, R. A.	Union Carbide Plastics Co.	River Road Bound Brook, N. J.
Delbourgo, Dr. R. D.	Sorbonne University	Paris, France
Dorsett, Henry G., Jr.	U. S. Bureau of Mines	4800 Forbes Avenue Pittsburgh, Penna.
Eft, N. W.	Babcock and Wilcox, Res. & Dev. Division	P. O. Box 835 Alliance, Ohio
Essenhigh, Dr. R. H.	Penn State	University Park, Pa.
Finney, C. S.	Eastern Gas and Fuel Associates	250 Stuart St. Boston 16, Mass.
Friedman, Raymond	Atlantic Res. Corp. Kinetics & Combustion Div.	Shirley Hwy-Edsall Alexandria, Va.
Gordon, Charles W.	Combustion Engineering Inc.	427 W. Randolph Chicago, Ill.
Grabowski, George J.	Fenwal, Inc.	Pleasant Street Ashland, Mass.

Hewes, Robert B.	Penn State	University Park, Pa.
Howard, Jack B.	Penn State	University Park, Pa.
Hubbard, D. R.	Factory Mutual Engineering Bldg.	Mt. Lebanon Blvd. Pittsburgh, Pa.
Jacobson, Murray	U. S. Bureau of Mines	Bruceton, Pa.
Jensen, John M.	Corn Products Co.	Argo, Ill.
Kingery, Dr. Donald	U. S. Bureau of Mines	Hampton Lane Allison Park, Pa.
Laffitte, Prof. Paul	University of Paris	Paris, France
Lee, H. C.	Ass'n Mill & Elevator Mutual Ins. Co.	400 W. Madison St. Chicago 6, Ill.
Lund, W. C.	Union Carbide Plastics Company	River Road Bound Brook, N. J.
Maltby, Frederick L.	Drexelbrook Consulting	1417 Edgehill Abington, Pa.
Meiter, Dr. E. G.	Employers Mutual of Wausau	6620 W. Capitol Dr. Milwaukee, Wisconsin
Merrill, J. W.	Union Carbide Plastics Company	River Road Bound Brook, N. J.
Miller, Earle C.	Riley Stoker Corp.	Worcester, Mass.
Mitchell, Earl R.	Mines Branch	562 Booth Street Ottawa, Canada
Moodie, Thomas W.	The Pillsbury Co.	1190 Pillsbury Bldg. Minneapolis, Minn.
Nagy, John	U. S. Bureau of Mines	4800 Forbes Street Pittsburgh, Pa.
Oravecz, Thomas A.	Pa. Dept. Labor & Industry	1414 Lab. & Ind. Bldg. Harrisburg, Pa.
Palmer, Howard B.	Penn State	University Park, Pa.
Putnam, Abbott A.	Battelle Memorial Inst.	505 King Avenue Columbus, Ohio
Ramadass, Venkataraman	Penn State	University Park, Pa.
Roberts, A. F.	SMRE	Harpur Hill, Buxton, Derbyshire, England

Robertson, A. F.	Nat. Bureau of Standards	Washington 16, D. C.
Schwab, R. F.	Factory Insurance Assn.	85 Woodland St. Hartford, Conn.
Schwartz, R. W.	Union Carbide Plastics Company	River Road Bound Brook, N. J.
Smith, Richard B.	Atomic Energy Commission	Washington 25, D. C.
Spicer, T. S.	Penn State	University Park, Pa.
Steidle, Edward	Federal Coal Mine Safety	811 Vermont Avenue Washington 25, D. C.
Strange, John P.	Mine Safety Appliances	100 N. Braddock Pittsburgh, Pa.
Thomas, P. H.	Fire Research Organization (U.K.)	Borhamwood Hertz, England
Thornhill, D. W.	Nat. Academy of Sciences Nat. Res. Council on Fire	2101 Constitution Ave. Washington, D. C.
Thring, Prof. M. W.	Univ. of Sheffield	Sheffield, England
Van Dolah, Robert W.	U. S. Dept. of Mines	4800 Forbes Avenue Pittsburgh, Pa.
Ventrone, T. A.	American Cyanamid Co.	Bound Brook, N. J.
White, Everett M.	Mine Safety Appliances Company	201 N. Braddock Avenue Pittsburgh, Pa.
Zulkoski, Michael	Penn State	University Park, Pa.

Total = 53

Organizations = 35

APPENDIX 2: Agenda

General Chairman: Professor M. W. Thring
Head of Department of Fuel Technology and Chemical Engineering, University of Sheffield, England; and General Superintendent of the International Flame Research Foundation.

Opening Speaker: Dr. Hylton Brown
Formerly Chairman, Committee on Dust Explosion Hazards, N.F.P.A.

SESSION I

Tuesday, 9:30 a.m., September 4, 1962 -- Facts and Figures:

Co-chairman: Mr. Donald Kingery, (U. S. Bureau of Mines).

The size of the problem in terms of human and economic loss; assessing current research facilities and requirements; and potential for expansion.

Speakers: Mr. D. Kingery (U. S. Bureau of Mines)
Prof. Paul Laffitte, University of Paris

LUNCH -- 12:30 p.m.

SESSION II

Tuesday, 2:00 p.m., September 4, 1962 -- Problems; Industrial and Academic:

Co-chairman: Dr. R. Friedman (Atlantic Research Corporation).

Discussion of research tactics to provide solutions for stated industrial problems.

Speakers: Mr. T. A. Ventrone, (American Cynamid Company).
and
Mr. D. Schwab, (Factory Insurance Association).

Dr. R. H. Essenhigh, (The Pennsylvania State University).

Wednesday, 9:00 a.m., September 5, 1962 -- Action.

Co-chairman: Dr. Earl R. Mitchell, Department of Mines and Technical Surveys, Canada

To discuss and examine possible courses of action, and ways and means to to defined objectives.

Morning and Afternoon, September 5, 1962 -- Summary and Closure

The Chairman: Professor M. W. Thring

Summarization of conclusions reached as to agreed upon actions and procedures.

APPENDIX 3: Objectives

1) to determine the size of the problem in terms of human and economic loss;

2) to decide what degree of intensification of research effort this human and economic loss should call for;

3) to assess current research facilities and their potential for independent expansion;

4) to assess what additional sources of funds and facilities might exist that could be utilized;

5) to consider the feasibility of cooperative research on either a formal or informal basis;

6) to decide what form the formal cooperation should take if this is approved;

7) to prepare the agreed strategy of research and agree on allocation of resources;

8) to consider the desirability of organizing some more formal machinery to arrange similar discussions or conference and/or presentation of technical papers at future dates. This might be arranged in cooperation with the Combustion Institute or with the bi-annual conference of the Directors of Safety-in-Mines Research.

APPENDIX 4: List of Papers

1. "Dust Explosion Research: An Appraisal", by Robert H. Essenhigh.

2. "Pioneering in the Study of Dust Explosions", by Dr. Hylton R. Brown.

3. "The Dust Explosion Problem", by Donald S. Kingery and Johy Nagy.

4. "Proposals for Experiments on Dust Explosions" by Robert H. Essenhigh.

5. "Electrical-Dust Hazards", Status Report S.R. 2 by the Instrument Society of America Sub-committee on electrical-dust hazards by T. W. Moodie (Chairman).

6. "Combustion Phenomena in Coal Dusts", by Robert H. Essenhigh: reprint from Colliery Engineering 38 (1961) 534; 39 (1962) 23, 65, 103.

7. "Dust Explosions in Factories: A Review of the Literature", by K. C. Brown and G. J. James. Safety in Mines Research Establishment - Research Report No. 201 (1962).

8. "The Thermal-Radiation Theory for Plane-Flame Propagation in Coal-Dust Clouds", by Robert H. Essenhigh and Joseph Csaba. Preprint of paper presented at 9th International Combustion Symposium (Cornell, 1962).

9. "Dust Explosions", by Robert W. Olson. Reprint from Mechanical Engineering, November, 1961.

APPENDIX 5: Vent Ratio Nomograph

Prepared by Mr. R. F. Schwab, Factory Insurance Association (Taken from the thesis submitted to the Faculty of the Polytechnic Institute of Brooklyn in partial fulfillment of the requirements for the degree of M. S. Ch.E.)

1. Origin: This nomograph has been compiled by the correlation of explosion tests in closed and vented explosion bombs.

2. Purpose: The nomograph can now be used to determine the vent ratio that would be required for some other dust for its explosion pressure to be reduced below some pre-determined safety level (determined, for example, by the structural strength of the walls, housing, ducting etc., where the dust is to be found). The vent, whether free or ducted, must, of course, be appropriately sited so as to prevent secondary incidents.

3. Method: To determine the appropriate vent ratio from the nomograph, input data must first be obtained experimentally by testing the dust on a laboratory scale using a closed explosion bomb. The vent ratios thus obtained, by the nomograph - identification of the experimental test data, can then be scaled up to apply to industrial equipment and buildings .

4. Data: The closed-bomb tests will provide the following input data:

(a) The maximum (closed-chamber) explosion pressure, A;
(b) (1) The maximum (closed-chamber) rate-of-pressure rise, R;
and or (2) The average (closed-chamber) rate-of-pressure rise, R'.

5. Use of the Nomograph: To use the nomograph, we require the values of A and either R or R', determined experimentally. We then adopt some appropriate values of the vented explosion pressure Y, that is our upper limit; and from the nomograph we then deduce the required vent ratio X, as follows.

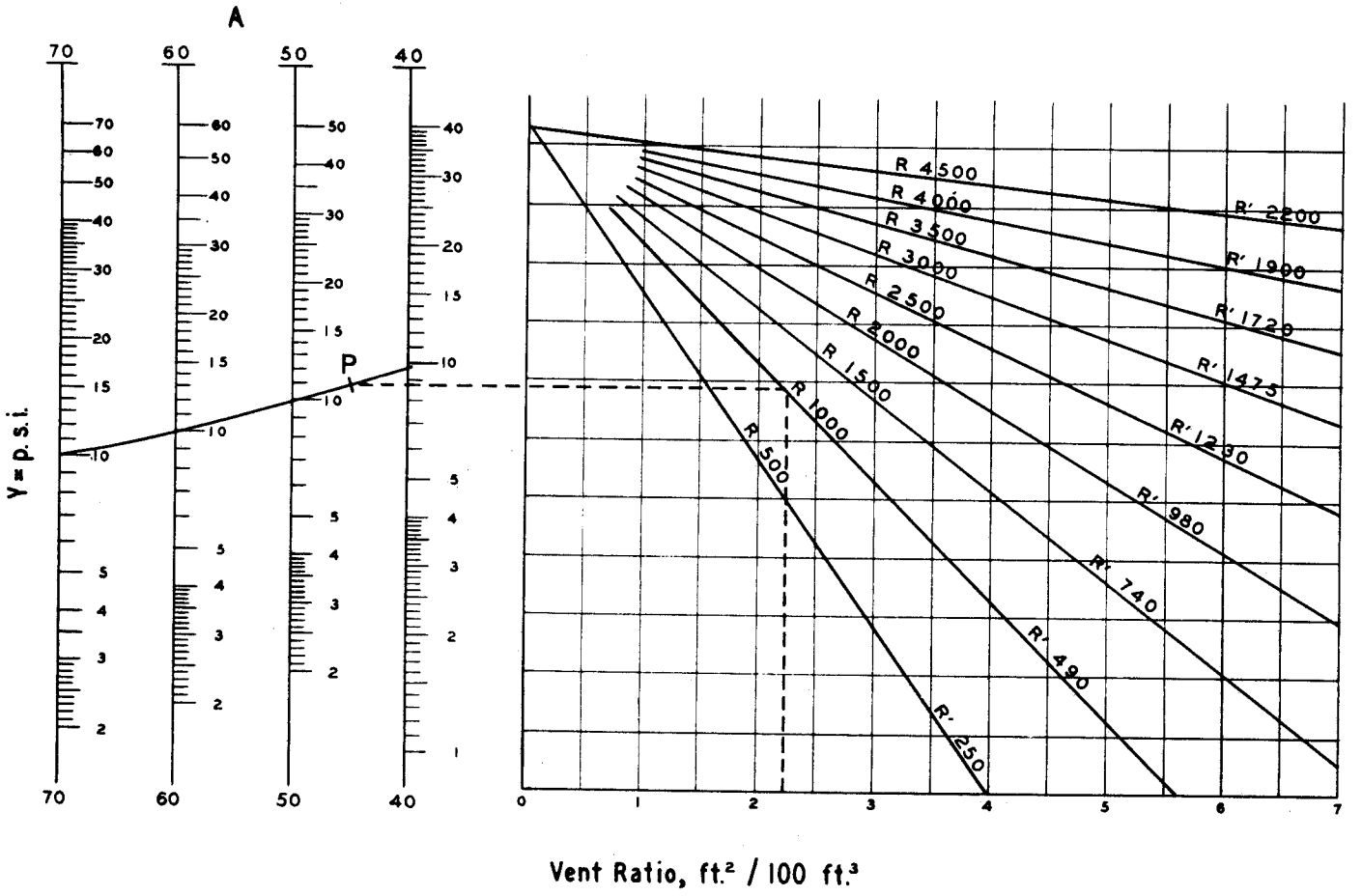
(a) On the A scales on the left of the nomograph draw a line roughly connecting the same Y values on each of the four A scales. The Y value is that adopted as the upper limit, let us say 10 p.s.i., (Note that the line is very slightly curved).

(b) Next, take the value of the maximum explosion pressure, A, determined in the closed bomb tests, and determine this A value by interpolation on the "Y" line already drawn. Let us say that A was 45 p.s.i., corresponding to point P.

(c) Now, proceed horizontally from point P onto the right hand graph to meet the appropriate R or R' line as determined by the experimental tests. Let us say this gave values of 1000 p.s.i./sec. for R and/or 490 p.s.i./sec. for R'.

(d) The appropriate vent ratio is then read off from the bottom (abscissa) scale. In the example quoted the value obtained is 2.25 sq.ft./100 cu. ft. (or more).

The system can also be worked backwards. If a vent ratio is predetermined by architectural and engineering considerations, then a value of Y can be deduced that will determine the nature of the constructional materials required to contain this pressure.



$$Y = \frac{A}{10^{\frac{X}{2.4425}\ \text{LOG}\left(\frac{5500}{R}\right)}}$$

$$Y = \frac{A}{10^{\frac{X}{2.4425}\ \text{LOG}\left(\frac{2700}{R'}\right)}}$$

X = Vent Ratio ft.²/100 ft.³
R = Max. Rate of Press. Rise. p.s.i/sec.
R'= Ave. Rate of Press. Rise p.s.i./sec.
Y = Explosion Press. p.s.i.
A = Max. Explos. Press. In Closed Chamber, p.s.i.

VENT RATIO NOMOGRAM