Keynote Address
THOUGHTS ON PYROTECHNICS
by
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Pyrotechnics is a fascinating subject for research because it sooner or later requires the investigator to apply most of the analytical tools that are available. Of course, one shouldn't overlook the appeal to the boy's love of noise and excitement that is present in much of our experimental work, whether we admit it or not. In addition to providing us with challenging problems and exciting experiments, pyro, in many cases, has afforded the only practical way to achieve the result that is desired. A special expertise is needed for the solution of the problems associated with these practical applications and the expert pyrotechnist appears to have become one of the "endangered species" in recent years. I hope the thoughts which I have presented in this paper may help to avoid his extinction. If they have any claim to merit, it is due to the people who have been my colleagues during forty years in ordnance research, which has included terminal ballistic effects, phenomena due to the detonation of explosives, missile destruct systems and incendiary ammunition functioning.

Much of my more recent experience has been with pyrotechnics, - to me, the most fascinating area of all ordnance research. In preparing this talk, I read several definitions of pyrotechnics, and would like to present them to you along with one of my own. It appears to be difficult to create a precise definition and I think it is important that we have a good one. I believe a clear definition of pyrotechnics to be a basic need if we are to attract the financial support that is needed for the conduct of research and development studies, studies that will increase our ability to design items which will function as expected, without relying so heavily on experience and testing to achieve the desired results.

After some comments on this matter of a definition of pyrotechnics, I will first discuss what I believe are some of the basic research areas on which attention should be focused, second, what I call the "image problem" of pyrotechnics and, in conclusion, the formation of an International Pyrotechnic Society.

First, let me present some definitions of pyrotechnics by the authors of several books on this subject. Brauer, in his "Handbook of Pyrotechnics", states that "Pyrotechnic means explosive devices in which explosives are burned rather than detonated". I find this definition too restricted and unimaginative because it lumps all kinds of pyrotechnics together in the category of explosives. I did not find a definition of pyrotechnics in the work by the Reverend Ronald Lancaster; the excellent quality of his work led me to ask the Reverend for his definition, which he very kindly furnished: "Explosives are reactions which perform at the highest speed and leave gaseous products. Propellants are similar to explosives, but somewhat slower. Pyrotechnics are reactions between two or more solids which produce flame or glow and which leave solid residues and gaseous products."

While Weingart does not specifically define pyrotechnics, he implies that it is the art and craft of utilizing chemical decomposition, particularly those reactions which occur at rates that produce burning or explosion. He specifically excludes detonations, except in rare cases.

Cackett in his monograph says, "Broadly speaking, pyrotechnics are employed to produce light ---, to produce smoke ---, to produce fire and incendiary effects? to measure intervals of time. They may also be required to function as propellants, igniters, and primers etc,." Although this is rather lengthy and, perhaps, more a description than a definition, I find it is close to the mark.

Shidlovsky has defined pyrotechnics as "--- the science concerning methods of production of pyrotechnic compositions and products, and of their properties". This is a circular definition, to be sure, but he goes on to say what is meant by "pyrotechnic compositions". "Pyrotechnic compositions, when ignited (or exploded), give illuminating, thermal, smoke, sound or reactive (jet) effects ---".

Ellern's definition follows a two page discussion of pyrotechnics in his treatise on Military and Civilian Pyrotechnics. He states, "Pyrotechnics is the art and science of creating and utilizing the heat effects and products from exothermically reacting, predominately solid mixtures or compounds when the reaction is, with some exceptions, nonexplosive and relatively slow, self-sustaining and self-contained." A very good definition, but a bit long.

Webster's Dictionary, widely accepted as a reliable source of definitions, say "the art of making, or the manufacture and use of fireworks". This surely is an understatement and oversimplification, which is of little help. One must seek the definition of fireworks, and finds this: "Firework; a device for producing a striking display (as of light, noise, smoke) by the combustion of explosive or flammable compositions especially for exhibition, signaling or illumination, typically consisting of a paper case containing combustible material ---".

Brock provides no definition as such, although he traces the history of pyrotechnics in a most interesting presentation.

I have presented these authorities' definitions- to illustrate the difficulty of arriving at a precise definition, which is evident in the variation among these. The best that can be done, I think, is to try to frame a definition that is acceptable to most pyrotechnists and that is basic enough to encompass all of the great variety of applications served by pyrotechnics. I have been rash enough to attempt this and to offer it for your consideration.

<u>"Pyrotechnics</u>: The science of controlled exothermic chemical reactions which are used to create timing devices, sound effects, aerosol dispersions, high pressure gas, intense heat, electromagnetic radiation, or combinations of these, and produce the maximum effect from the least volume. High explosives are excluded, but initiators are included". Your comments and improvements on this definition will be welcomed.

Next, I would like to present to you the areas of research which I believe should be pursued most assiduously. It seems that the materials of pyrotechnics have always been regarded with suspicion, fear and some awe by the general public, from the times of the alchemist in the Middle Ages until now Knowledge of the applications of these materials in pyrotechnic devices has been restricted to a few people, and today we see the solution of production problems in military pyrotechnics hampered by the restrictions of "Security Classification", and the production of display fireworks a closely held commercial secret. As a consequence, much useful research that could be performed in university laboratories is not done, because university personnel must publish their results in the open technical literature. Besides the loss of basic information for the pyrotechnist which follows from this lack of attention, another result is the general lack of knowledge concerning pyrotechnics that prevails among those who have no experience with it. My esteemed colleagues in the chemistry and physics departments of my own university have, on occasion, referred very disparagingly to it as "dirty research" -whatever that is - or as "Oh, you mean fireworks", or "that's kid stuff". Furthermore, most university professors are unaware that many thesis subjects suitable for students who seek advanced degrees can be found in the problems now facing pyrotechnics, e.g., theses of Douda and Chazal. The advancement of pyrotechnics as a science is slowed because these subjects are not being investigated; consequently, badly needed research is not done with any plan or logic. If it is done at all, it is usually a result of the need to solve an immediate problem and not to lay a broad foundation for the future.

Why do I discuss all of this? Because I believe that today pyrotechnics is at a point of decision. If it is to grow and be recognized as one of the major subdivisions of science and engineering, to be considered on an equal footing with specialties such as perfume or polymer chemistry or explosive forming, a change in its image must be achieved. Otherwise it will continue to limp along as part black art and part experience, plus a little science. Furthermore, I think a change in the way pyrotechnics is perceived by the military is essential for its survival in the future. So long as black powder rockets could be fired a few hundred meters to terrify the enemy, or to set his haystacks on fire, the technical demands made of the pyrotechnist were rather modest. Until WW 1, the demands of the military on the pyrotechnists' skills were simple; reasonably pedestrian chemistry or physics served him quite adequately and the raw materials and processing that were needed were relatively easy to obtain as standard items of commerce. That time has passed. Although the complexity of pyrotechnic devices has increased greatly in response to the growing difficulty of the problems for which they provide solutions, our understanding of the fundamental processes of pyrotechnic systems does not appear to have kept up with these demands. It is relatively easy to create a red signal flare, but it is very difficult to create an infrared decoy flare that satisfies all of the requirements of storage, safety and effectiveness as a decoy for a guided missile designed to seek the hot regions of a target. It is no longer sufficient for the pyrotechnist to mix saltpeter, sulfur and antimony sulfide with some gum arabic solution to produce a "white" signal flare. Today, he must understand spectroscopy of the combustion process well enough to identify the emitters that create a green flame when certain mixtures which contain barium are burned and the effect of flame temperature on the purity of the color. He must understand physics and physiology well enough to compute the color purity of the green flame, and physical chemistry if he is to improve it. But this kind of information would never have been obtained by the empirical methods which characterized pyro up to about 1940, and which are still used in many cases. Information of this sort is obtained only by careful laboratory work, guided by the best available theory and the latest techniques of physical chemistry; these requirements are frequently best satisfied in the laboratories and graduate study programs of our universities. It is just this kind of study, as I mentioned earlier, that can be done as thesis research for advanced degrees - but it is very rarely done. Sometimes it is done as a part of a practical study which has some important and immediate objective that can be more quickly achieved by applying the results of a directed research study. This is usually a small ancillary research study, which generally results in supplying only one more bit of data not the broad data base that would be a firm foundation for future problem solving. Useful, of course, but far from adequate; worse; it may very likely be available to very few persons because of publication restrictions which are usually placed on studies conducted with government funds whether they are performed at a university or a government laboratory. I am not aware of any research that is funded by the display fireworks industry, but if it exists, I'm sure that in most cases the results are kept for the sole benefit of the sponsor. As a consequence of these government and commercial restrictions, the science and technology of pyro progress very slowly. I am suggesting that there are research studies that should be done because they are of interest to everyone who is involved in pyrotechnic manufacture. The areas I believe to contain these fundamental problems of pyrotechnics which should be the subject of a continuing research program are: (1) properties of materials, (2) reaction processes, (3) flame structure. In addition, there are two areas of common need and interest which require data from laboratory investigations, and sometimes some specific testing, but which are not usually included as research subjects. These are: (4) standards and (5) safety. Finally, to support these there is a requirement for (6) formalized special education and (7) a recognized technical society to help focus our efforts.

In the materials category, I believe there is a need for research that will first define the properties which are of interest specifically for pyrotechnic uses, that is, to determine what must be quality controlled to achieve reproducible behavior when the materials, including those used for containment, binders or sealants etc., are used for pyrotechnics. I believe this task has not received the attention it should and that it has only begun. If studies of material properties had received adequate attention and support, the matter of-consistently manufacturing black powder to perform the same way in all of its applications probably would have been solved long ago, and it could be bought from any supplier anywhere, with complete confidence in its performance in the device in which it is used. Such is not the case. Neither would the manufacture of delay trains ~e up t by a change in the source of, say, tungsten powder. You can surely add many examples of your own. The point of all this is simply that we do not understand the materials and the reactions of pyrotechnic compositions well enough to write good specifications for the quality control of the basic ingredients. Perhaps we can never accurately specify the quality of every ingredient, but a good research program would certainly improve many specifications and, probably, lower material costs. The specification of "Chemically pure" or "Reagent grade" material is often simply an indicator that the user is ignorant of the impurities that are really important for his purpose and he therefore takes the costly approach of minimizing every impurity.

Reaction processes are closely connected with some material properties, for example, melting and boiling points. In addition they define specific stages in reactions that must be understood before an accurate and useful model can be constructed for the purpose of predicting the changes in performance which follow changes in formulation or assembly of pyrotechnic items. As an example, consider an illuminating composition of magnesium, sodium nitrate and a binder. It is customary to speak of stoichiometric compositions of the components and to estimate the radiant output as though the combustion reactions were all proceeding in the gaseous, or at least in the liquid, phase. This is not usually the case and it leads to some highly erroneous estimates of the radiant output If combustion really were proceeding from a stoichiometric basis, the composition of the ambient atmosphere would have no effect on the radiance of the flame. In fact, it does have an effect. When the ambient air is replaced by an inert gas, such as argon, the output may be reduced by a factor of one hundred or more. Examination of high speed motion pictures of the burning surface of the flare helps to explain this by showing what a moments' thought would predict. Even though the solid ingredients are indeed present in the proportions computed from some assumed reaction equation, they cannot react stoichiometrically because the nitrate melts and surrounds the magnesium particles, which are still solid. What is the concentration of fuel and oxidizer at this interface? What is the real oxidizer --- nitric oxide, nitrous oxide, or something else? No one knows, yet it is certainly of crucial importance to the progress of this combustion reaction. It is reaction processes in this sense that I believe should receive serious attention in a continuing pyro research program. The luminous output of the flame from this reaction is due mainly to excited sodium atoms and any process that quenches them will reduce the luminosity. Therefore, one must also include consideration of atomic processes of this nature in a good model of flame reactions.

The structure of pyrotechnic flames is of great importance to the manufacture of incendiaries, initiators, illuminating/signal/decoy flares, yet it is almost completely unknown. I will define flame structure in the context of this paper as the chemical and physical composition and the extent of the flame; that is, the spatial distribution and the nature of the chemical species in the flame and the gas/particulate velocity and temperature at every point. Years ago efforts were made by the U.S. Air Force and are currently supported by the Navy to establish data bases on specific flames to obtain data that can be used to create a theory for the prediction of radiant output as the percentage composition and the physical size are varied. As Far as I know there is no continuing effort to obtain the data that will be required for the establishment of a general flame model of practical use to pyrotechnists. Many papers and books have been published on the structure and properties of flames -but there are very few on flames from pyrotechnics. By their nature, pyro flames are transient and full of particulates - dirty flames that may be almost opaque - and therefore not attractive subjects for research when there are much simpler and easier systems to study.

But if we are ever going to acquire the ability to predict with accuracy the static and dynamic radiance of a flare from its composition and construction, continuing studies of the flame structure produced by pyrotechnic devices are required to provide the data for a model, or models with which such predictions can be made. These studies are challenging to the theoretician because of the boundary conditions and extreme temperature and composition gradients to be modeled and the reactions that must be identified. The challenge to the experimenter is equally great because of the difficulties in measuring temperatures, species, concentrations and the spatial and temporal variations of these. Studies of this complexity will require the commitment of funds to a long term program; year-by-year studies cannot conquer the problem.

There are at least two kinds of standards required by the pyrotechnist. One is a standard of measurement, or testing, so that the results from different laboratories may be compared without the question arising "are the results truly different, or is the difference due to the measurement techniques?" An outstanding example of this need for standardization is the measurement of radiation. Radiation measurements in the range from ultraviolet though infrared are among the most difficult, even when the source is a nice cooperative one with an "infinite" lifetime, such as an electric lamp. Unfortunately, our pyrotechnic sources are usually transient, unstable, and generally frustrating to work with; nevertheless, the need for good, comparable radiation measurements is of great technical and economic importance. Although there are documents of a quasi-official nature (e.g., Parish & Dinerman) which attempt to state what the measurement conditions should be, they are of very limited authority and acceptance. Unfortunately, many times it becomes necessary for those of us who are quasi-competent to make these measurements. I'm afraid much disagreement in the results from different measurements is due to this quasi-competence and to people working without the help of the experts. This help is one of the essential parts that would have been incorporated into a detailed specification of the manner in which the radiation is to be measured. Much the same comment can be made concerning burning rates, frictional and electrostatic sensitivity, impact sensitivity, chromaticity, etc. It is necessary to come to an international agreement on the meaning of terms and the methods of measurement, and then to document the test methods in sufficient detail that even the quasi-competent worker can obtain results. Perhaps then it will be possible to settle many long-standing arguments as to which device is the best.

A second form of standard is the purchasing standard, or, as it is often called in the U.S., a "Mil Spec" - a military specification of quality. As I mentioned earlier, much money can be saved by knowing what elements of a specification must be closely controlled and which need little control. At present, there doesn't seem to be any way to write accurate specifications for purchasing such simple things as elemental tungsten powder for use in delay trains, or sodium nitrate for illuminating flare compositions, simply because the reactions in which they are used are not well understood. Perhaps, when they are, standards can be written to insure that changes in the source of supply will not cause changes in the performance of any item in which the material is used. The problem is not entirely a technical one and, probably, national rather than international committees will have to write the specifications for each country because of the political and economic factors which are different in each country and affect the decision as much as purely technical factors. Although the standards really should be based solely on good engineering practice, sometimes it will be necessary to use alternate materials because they are preferred for political or economic reasons and the specifications must be able to accommodate these nontechnical requirements.

Safety should be based on an understanding of the fundamental mechanisms which are responsible for ignition, or the initiation of an explosion. Much work has been done on these subjects which, in conjunction with the increasing concern of both industry and government over loss of life and injury to personnel, has certainly resulted in much better safety regulations than were followed some years ago. However, we still depend heavily on precautions which are the result of experience rather than the predictions of a good theory - avoid sparks, whether mechanical or electrical, impact, friction etc. Our quantization of how much friction one must avoid, or how energetic an electric spark, is rather poor - by which I mean that it is variable from one laboratory to **another** and from one test to another. In other words, the experimental determination of these quantities would appear to be based on a very limited understanding of the true nature of the phenomena.

I think much of the variability can be removed by improved, standard test methods which are well defined and accepted for use in all pyro laboratories and factories. Some tests we ran to determine the sensitivity of various materials to ignition by an electric spark exemplify a rather bad test method. A spark passed from a pointed tungsten electrode though a thin layer of the powder to a flat steel plate; ignition was determined by the appearance of a flame. This is a standard test method but great variability was found in the results. Some of the variability could be assigned to the effects of changes in the relative humidity of the air, which was not controlled. My own opinion is that the varying energy in the spark not only affected the energy available to ignite the powder but also affected the dispersion of the powder because of the changing intensity of the acoustic and thermal effects in the air around the spark. Watching the tests, some of these changes could be seen with the unaided eye; as the energy supplied to the spark increased, the size of the cloud of powder it created also increased, but the increase was greater for the less dense materials. The test is simple to perform, but I think without much value as a guide to the establishment of electrical safety regulations. At present, we must often rely on data from tests such as these that are designed to meet the needs of others, such as the coal mining industry and from tests that differ in their d,-rails when performed in different laboratories**.** Good, meaningful standardized tests which give consistent results in every laboratory will greatly improve the protection that can be provided for workers and plant equipment engaged in the production of pyrotechnics. It should be the objective of on-going, well funded research studies to create such tests. I would expect these studies to be useful in achieving better ignition, as well as in their primary objective of preventing it. Uniformity of safety practices would be another result of general acceptance of good test methods, especially if some effort was put forth by a generally accepted body to draft the standards to be followed.

It may appear from these comments that I am not aware of the existence of a vast literature on combustion and, I am sure, there is indeed a great deal of it with which I am not familiar. However, the bulk of the papers on combustion I have seen do not deal with pyrotechnic subjects but with propellants, or explosives, or even more general combustion systems than these. For example, there is an interesting collection of papers edited by Ingo May that has been published by the U.S. Army Ballistic Research Laboratories on the subject of ignition. The papers were prepared in response to recognition of real-world problem areas which involve ignition in an attempt to fill basic information gaps and more efficiently solve problems. The general area of concern to which these papers were addressed was propellants. Some excellent research was reported in them, but it was done on propellant compositions, not on pyrotechnic compositions. Consequently, while the material presented and the experimental techniques that were used are of considerable general interest to pyrotechnists, there are few specifics that can be employed to improve the performance of pyrotechnic devices. We should certainly borrow as much as possible from our colleagues in explosives and propellants research, but that does not avoid the necessity of doing our own work. Since black powder is an important component in pyrotechnics as well as a propellant, I will paraphrase some of the comments Ingo May and Austin Barrows made in the introduction to their work on ignition. "Black powder remains one of the great examples of the triumph of art over science. It remains an important part of many ignition trains and yet the production of it is to a large extent a "black" art. The residue is quite a serious problem in some applications; other problems are the manufacture of it in safety and with reproducible characteristics. After hundreds of years of use, the chemical and physical properties of black powder are still not adequately characterized." Much the same comment would apply to pyrotechnics in general.

While pyrotechnics can borrow much from the work in other areas of combustion, the problems are still sufficiently unique to our field as to require solution by research directed specifically to that end. I believe that a formal course in pyrotechnics would go a long way toward providing solutions to these problems. It should be taught at a university and result in the granting of Masters or Doctoral degrees in Pyrotechnic Science and Engineering. At present one becomes a pyrotechnist by chance and usually with one of the engineering or scientific disciplines as background. The novice pyrotechnist is exposed to many hazards and may soon view essential experimentation as to`' dangerous when, in fact, it is not. On the other hand he may ignore real dangers and injure himself and others. He is also prone to re-invent the wheel", because he doesn't know the history of pyrotechnics. In contrast, a graduate with his degree in Pyrotechnic

Science and Engineering would be competent, safe, knowledgeable, and capable of making useful contributions to the solutions of his employer's problem soon after his employment. If there were a course like this, it would do more than provide trained professionals; it would also result in recognition of Pyrotechnic Science and Engineering as an area of professional competence, just as chemical engineering or microbiology are recognized. It would then follow that studies which would be beneficial to pyro would become a fruitful source of material for graduate research problems and the resulting work on these would soon begin to provide answers to the problems of variable material properties, reaction processes and flame structure. Furthermore, this would be a source from which one could expect the appearance of talented young workers with new ideas in commercial pyrotechnic applications. A greater commercial use of pyrotechnics would expand the market and reduce the dependence of the manufacturer on military programs for his income. The resulting stabilization in the demand for pyrotechnic products would certainly improve the stability of employment and of funding for in-house research, in contrast to the present variable need for competent personnel. The faculty that teaches the courses would be a continuing resource as a depository of the knowledge which is now kept in the memories of older pyrotechnists and lost when they leave the field. I hope you will agree that it would be beneficial to both the manufacturer of pyrotechnics and to pyro research laboratories if some university could be persuaded to take the initiative of establishing a degree in pyrotechnic science and engineering. At one time I attempted to do this at my own university and nearly succeeded, but was blocked by the tenor of the times which caused the administration to fear student reaction to programs which had military overtones; I don't believe this would be true today. Since that time the College of Engineering has been closed and I have no desire to make another attempt. If it is to happen, it will require a champion at some university to initiate the program and that champion will appear only with continuing effort by the pyrotechnics community. You must convince the university administration that a need exists, that it will continue, and that graduates will find employment. You may have to secure guarantees from government agencies who are users of pyro, that they will provide students for the first years of the degree program as a means of supporting the expense incurred by the college. In Europe the educational system differs from ours so that I cannot comment on the nature of the effort that would be needed, but I am sure that my European colleagues will know what is required in their own countries.

Perhaps the first step in the direction of establishing university degrees in pyrotechnics and solving some of the technical problems would be the creation of a group which could speak for the entire industry, as is true in the United States for societies such as the Institute of Electrical and Electronic Engineers, the Illuminating Engineering Society the Sporting Arms & Ammunition Manufacturers Association, and the Institute of Makers of Explosives. Such an "International Pyrotechnic Society" should, I believe, supply several very much needed services to its members. It should promote and facilitate the exchange of information concerning the art and science of pyrotechnics among all interested persons. It should create and maintain an information bank which can speed or simplify a member's search for information on a pyrotechnic material, composition, device, manufacturer or research study. It should sponsor meetings on pyrotechnics at such intervals and on such subjects as may be appropriate to further its purpose. It should encourage pyrotechnic education and educators. It should establish standards of safety, performance and quality for pyrotechnic materials, devices, manufactures and research. And, I would hope, it will publish a journal - even though at first it might appear only annually.

The group which is now responsible for presenting future International Pyrotechnic Seminars - what I am told my European colleagues call "the Denver meeting" - are also preparing the constitution and by-laws for an International Pyrotechnics Society. Those who would like to help may write to me in Denver and I will see that you receive copies of the constitution and by-laws. Your constructive comments and criticisms will be most welcome.

In conclusion, I would like to summarize by saying that a good definition of pyrotechnics seems to be essential as a means of discriminating between it and closely related subjects, such as propellants and high explosives. I am convinced that an International Pyrotechnics Society and graduate degrees in Pyrotechnic Science and Engineering are essential foundation blocks for the support of ongoing research on materials, reaction processes, flame structure and the preparation of accurate purchasing specifications. While I believe that safety is, fundamentally, an attitude or habit of thought, much can be done to protect the individual from lapses of good practice when better information becomes available from the research programs on standards. I have enjoyed my experiences with pyrotechnic research, perhaps because, like most boys, I like to hear a good loud "bang", but more because it is a challenging field that employs almost every scientific and engineering discipline.

You have been very patient, but you have listened to me for long enough, and it is time to say thank you very much for your courteous attention and for the honor of addressing you. Thank you.

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