Conclusion

At the conclusion of this discussion it is important to keep in mind the influences of all the complex processes involved in visual spatial localization, among which stereopsis is only one. The various factors and cues for this spatial localization interact with, complement, reinforce, and perhaps even inhibit one another, depending upon the varying visual surroundings of the moment and upon the physiologic perfection of the visual apparatus. In one's daily work probably no single factor or group of factors dominates at all times. "Any one who knows how pliable our spatial visual perceptions are under the influence of various conditions of observation and under the influence of past experience, taken into account consciously or unconsciously, should not be surprised at the multiplicity of results of observations on different objects and with different observers" (see *18*).

It is not surprising, therefore, that if one selects any single visual factor and attempts to find its specific importance in a subject's ability to perform a given complex task, often no correlation or only a poor correlation is found. In particular, one can refer to the poor correlation that obtains between stereoscopic acuity, as measured on a particular test apparatus in the laboratory, and the flying ability of the aviator. This low correlation and the equivocal associations reported in the literature have been construed by some to mean that stereopsis is of little value to the pilot, but the conclusion seems unwarranted and unfortunate.

In this article I have presented (with a degree of oversimplification) some of the basic and yet up-to-date concepts regarding visual perception of space. A number of perplexing problems have been pointed out, with methods of approach to several of them. In such a discussion it is difficult to avoid becoming enmeshed in the psychology and philosophy—and above all, the semantics—of the general field of perception. Even so, I feel that it is best to adhere to those concepts that allow one to approach the problems of visual perception in a manner providing, as nearly as possible, a physiologic basis for understanding them.

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Rockets, Resonance, and Physical Chemistry

The problems encountered with solid-fuel rockets bring together an amazing variety of disciplines.

F. T. McClure

From time to time one hears much discussion of the importance of interdisciplinary endeavors. In recent years, in particular, numerous attempts have been made to encourage and inspire such efforts. This concern clearly arises from the fact that as science continually broadens its base and vastly increases the sum of our knowledge, there is a concurrent tendency toward increasingly narrow specialization. While on the whole such specialization has been good and, in fact, essential to progress on the many individual fronts of science, it is nevertheless true that many of the problems which face us do not fall neatly into the defined specialized categories. Thus, there is great need to bridge the gap between the specialties in order that all pertinent information may be used in formulating a solution of the problem at hand. The breathtaking rapidity of scientific and technological advances in these days, and their impact on our whole society, has apparently created a more widespread awareness of this question. It is in this context that the modern pleas are to be understood.

Sometimes, however, there appears to be a tendency to regard this problem as something qualitatively new in man's experience, and so requiring a new kind of man. I think that this is a mistake. Scientific history is filled with examples of the outstanding contributions of men who have cut across formalistic and pedantic lines—men who have brought fresh viewpoints from one field into another and have solved vital problems which did not appear to merit the attention of experts in any one of the then accepted disciplines. Further, I venture to suggest that it is the generalists who have provided opportunities for specialists to find fruitful areas, and not the converse. I would be surprised if this view were not considered so obvious as to be trite, particularly among chemists aware of the history of their profession.

I could easily forgive a reader if he were now inclined to ask what this bit of philosophy has to do with my topic. Merely this: the science of solid-fuel engines provides a modern simple example—and there are many more so-

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phisticated ones—of an area in which the degree of specialization of the investigator can all too easily be inversely proportional to the value of his contribution. I really have two points in mind. First, a surprising variety of disciplines converge in the design of a rocket engine. I am not here referring to all the complex gear aboard a missile. I am referring only to the engine. These disciplines appear in such an interwoven fashion that they essentially become inseparable. Second, there is a group of physical scientists whose activities have always forced them to be abreast of, and capable of working in, a number of fields. These are the physical chemists (and in this context I view the chemical engineer as a practitioner of physical chemistry). It is not my purpose to dwell upon the activities of physical chemists in their central role of bridging the gap between physics and chemistry. I merely want to point out that they possess the breadth required to attack the major problems of the field in question. Suffice it to say that the names of many outstanding physical chemists are prominent in the list of contributors to the science of solid-fuel rocketry (*1*).

The Solid-Fuel Rocket

A rocket may be visualized as being something like a champagne bottle. The high-pressure gases within the bottle are expelled through its neck. The forward thrust of the rocket is the recoil from the expulsion of these gases. In order that this forward thrust may continue there must be provided a method for continuously regenerating high-pressure gases which, in turn, will be continuously expelled through the neck of the bottle. In the case of the solid-fuel rocket, on which we will focus our attention, the source of these gases is the burning of a solid fuel. A block of solid material, containing chemical reactants in rather intimate mixture, continuously evolves hot propulsive gases. Typically, these gases are at a temperature of the order of 3000°K.

Now, in the uses to which rocket engines are normally put, the penalty for excess inert weight is very severe. Ideally a rocket should be all fuel, and failure by more than a few percent to achieve this goal tends to constitute a disaster in the ultimate mission of the rocket engine. For the practitioners of metallurgy, for the specialist in ceramics, for the connoisseur of plastics, for the purveyor of glass fiber, and for the inventor of adhesives, this engine has provided a major challenge. New materials, new techniques for fabricating the materials in new fashions, and new methods of joining metal to metal or metal to other material have been required. All these materials, and their bonds, must be compatible with an atmosphere of a chemically very reactive gas at high pressure and high temperature. They must be fabricated in shapes and sizes to meet the needs of the rocket ballistician. These needs are often exacting, sometimes even more exacting than the ballistician himself realizes.

But it is not my intent to dwell on the difficulties of designing and building a satisfactory rocket. Suffice it to say that this is a very intricate business which has required major advances in many technologies and which is essentially unrelated to the much-publicized activities of high school seniors supported by local rocket clubs. Seriously, it is no business for children.

Rather, let us turn to the areas of interest to the chemist. I shall attempt to outline where the chemist has contributed to the development of solid-fuel rocketry, and to indicate some of the extremely interesting and complex problems that remain.

As I have previously noted, it is the ejection of the propulsive gases which provides the recoil responsible for the thrust of the rocket engine. What properties of the gas are important in this respect? What determines how much impulse one obtains from the ejection of a given mass of gas? This is mainly determined by the enthalpy, or heat content of the gas per unit mass. In simple terms, it depends on the temperature of the gas and upon its molecular weight, among other things. One could reasonably expect, therefore, that this important property of a fuel could be estimated if one knew the heat of formation of the solid fuel and its atomic composition. This expectation is correct. One can calculate the specific impulse of a fuel from just this information, provided one uses the full technique of statistical thermodynamics and has a supply of spectral and other data adequate for estimating with accuracy the properties of all the interesting component molecules of the rather complex propulsive gas. This was a problem attacked by Hirschfelder and his colleagues during World War II, and in the years since, it has, to a considerable degree, been reduced to a routine.

In these remarks it is assumed, however, that all of the gas-phase chemical reactions involved are so rapid that local chemical equilibrium is preserved throughout the process. Certainly one wants to release as much energy as possible during the time the gas resides in the combustion chamber. Even then there are questions. The flow of the gas through the nozzle (that is, the neck of the bottle) occurs in a time that is ordinarily less than 1 millisecond. At the same time, the temperature is dropping very rapidly, owing to the adiabatic expansion. There is thus a real question as to whether equilibrium will be maintained throughout the process so that the energy stored chemically, and in the internal modes of the molecules, will become available as directed kinetic energy. While a number of valuable studies have been made in this area, the question must be considered still open with respect to at least some fuels, and of considerable importance for rocket engines designed for exacting missions. Here the pertinent areas of science are the physics of relaxation processes and (perhaps more important) the chemical kinetics of the high-temperature chemical reactions—both areas in which much remains to be learned.

Combustion of the Solid

I have thus far discussed the properties of the propulsive gas and the problems associated with it. We have been assuming that the steady combustion of an appropriate solid will produce this gas as needed. It is time now to turn to the question of the properties which this solid must have. The first thing to note is that we would expect the rate of evolution of hot gases from the solid to be a function of the environmental conditions. The pressure dependence of the burning rate of the solid is a very vital feature of a rocket fuel. This may be seen in the following considerations. The mass rate of flow of combustion gases from the rocket is, it turns out, directly proportional to the pressure of the gas within the rocket. Now the rate of the burning of the fuel—that is, the rate of production of propulsive gases—is also a function of pressure. Therefore, we might hope to find a pressure at which the rate of production of gases is equal to the rate of exhaust. However, we require more than this. If the pressure is too high, the rate of exhaust should exceed the rate of generation, so that the pressure will fall, and on the other hand, if the pressure is too low, the rate of generation should exceed the rate of exhaust, so that the pressure will rise. Reference to Fig. 1 makes it clear that a propellant, to be satisfactory, must have the following characteristic: the rate of evolution of gas must have a pressure dependence which is less steep than a direct proportionality in the neighborhood of the steady-state operating pressure. In other words, if we represent this rate of burning of the solid as proportional to the pressure to some power, then that power must be less than unity. It is not only necessary that that power be less than unity but highly desirable that it be as low as possible.

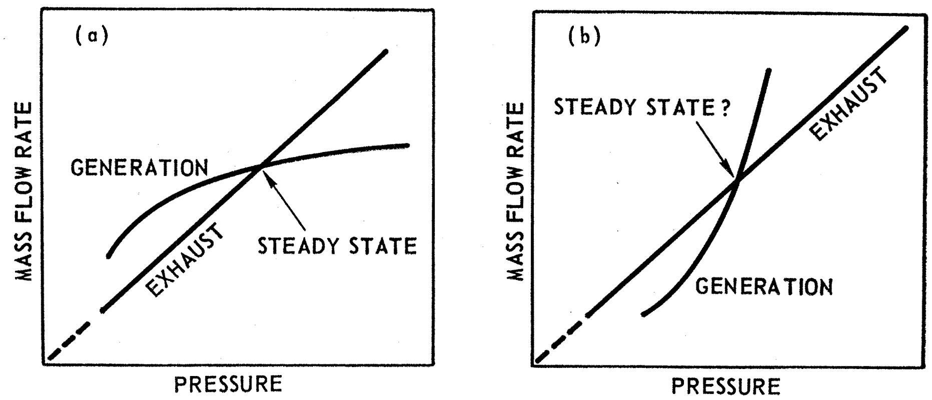

Fig. 1. Relationship between the rates of gas generation and gas exhaust in a rocket. (*a*) Stable steady state; (*b*) unstable steady (?) state.

In addition to depending on the operating pressure, the rate of burning of the solid propellant depends on the temperature of the solid propellant (this is, for all practical purposes, the temperature which the propellant had attained prior to ignition of the motor). Again, since the rocket is expected to perform well under a wide variety of conditions, it is highly desirable that this temperature coefficient of the rate of burning be as small as possible.

Now, over the years various empirical means of formulating propellants to give desirable properties with respect to burning rate and the pressure and temperature dependence of the burning rate have been devised. To some extent these techniques are understood, but to a very large extent they remain empirical. This raises another matter which the physical chemist faces —that of understanding, in a quantitative manner, the combustion or burning of a solid.

From the standpoint of the physical chemist, what is the problem? If I may be permitted to assume an ideal situation where all of the materials are thoroughly premixed, thus avoiding problems of mixing by diffusion and so on, then the problem may be described as follows. First, it is known that practically all of the activity of interest takes place in the extremely thin layer immediately at the surface of the solid propellant. The thickness of this layer is a matter of some argument and probably varies from one type of propellant to another. However, it seems fairly clear that in almost all cases this layer is less than 100 microns thick. That is, all of the chemistry, and in fact physics, of the process of steady combustion of a solid propellant occurs in a layer that is less than 1/250 inch thick. We observe the transformation, within this very thin layer, from cold solid to very hot burned gases. Thus we are in a region where the temperature gradients are of the order of 1 million degrees per centimeter, or to put it in terms of the gas evolving from the surface, where the rate of temperature increase of the gas as it moves from the surface to the hot zone is of the order of 100 million degrees per second. Now this is a far cry from gradients in the well-thermostated reaction vessels of the thermodynamicist or chemical kineticist, and we have far too little experience with chemistry in such fantastic gradients.

We might go a step further and note that this already very thin layer can be divided, in the mind, into at least four subregions. This is illustrated in Fig. 2. To start from the side of the cold solid, there is a region in which the solid is warmed by the flux of heat from the hot gas. Then, near the surface the solid enters a region, presumably quite narrow, in which it cracks or decomposes to form gaseous products at temperatures that are somewhat elevated but still well below the final flame temperature. Next there is a region where these gases are warmed to a temperature at which they react rapidly with one another in the fourth, or gas phase, combustion zone, to produce the final hot product gases. We thus have a system in which there is mass flow forward which is controlled and sustained by the flux of heat backward. Together these two processes, mass transport forward and heat transport backward, form a closed loop which seeks its own overall rate. This rate, however, will depend on the boundary conditions of this very small system—for example, on the pressure of the gases and the temperature of the solid. In view of the fact that we

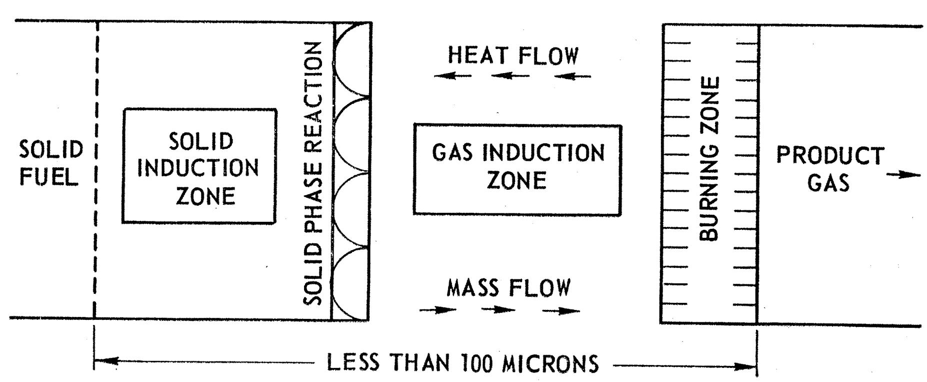

Fig. 2. Schematic diagram of activity in the thin region at the burning surface of a solid propellant.

know very little about even the simplest chemical reactions under such flow conditions, and that we have only the slightest knowledge of details of the chemical reactions involved in these particular systems, it is perhaps not surprising that physical chemistry has not yet given a complete and quantitative explanation of the pressure and temperature dependence of practical propellants. Nevertheless, if there is to be a scientific knowledge of this subject, it must come from an understanding of the physical chemistry of this extremely thin zone.

Acoustic Resonance

Now let us suppose that the designer of the solid-fuel rocket engine has been meticulously careful with respect to the matters discussed above. He has selected a propellant with all the appropriate properties, after experimental testing in laboratory equipment. His chambers have been tested hydrostatically for ability to withstand the design pressure with a reasonable safety factor. The geometry of his design has been carefully checked by several assistants. All the criteria for a perfectly satisfactory motor have been met. The motor is designed and built. Comes the day of the test. The countdown proceeds, the firing button is pressed, and the whole thing blows up. Or perhaps he is not that fortunate. Perhaps the first test is completely successful. Perhaps he even has repeated successes under those particular firing conditions. Then a little later, just after everyone is thoroughly satisfied, a slight change is made. A slightly different firing temperature is used, or some very insignificant modification is made in some trivial internal component. The button is pressed, and the motor blows up. Strange as these events may seem, they are entirely too common.

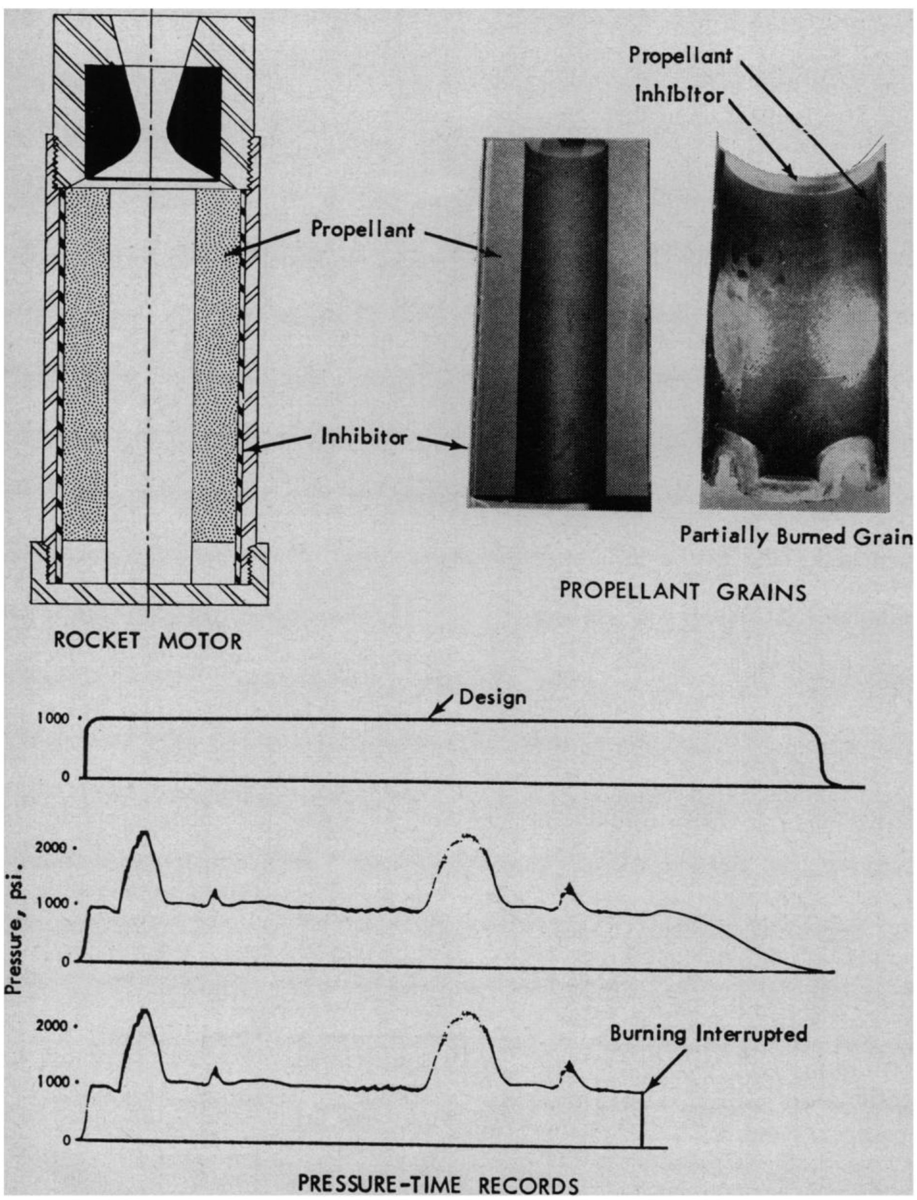

Fig. 3. Consequences of acoustic resonance in a solid-fuel rocket (*2*). (Top left) Schematic diagram of motor with propellant; (top middle) longitudinal section of propellant grain; (top right) longitudinal section of partially burned grain from interrupted burning. Pressure-time records: (top) expected pressure-time history of burning; (middle) observed pressure-time history of burning; (bottom) pressure-time history of interrupted burning.

In Fig. 3 are portrayed typical results (*2*) which the experimenter might find if he examined the situation more closely. Figure 3, top left, is a schematic diagram of the rocket motor before firing. Figure 3, top middle, is a photograph of a longitudinal section of the propellant grain used. This is in the form of a cylinder which burns on the inside surface and at the ends. There are slots in one end, designed to cause regression of the ends, as the cylinder burns, in such a manner as to balance the increase in diameter and keep the burning surface very nearly constant. The top graph (Fig. 3) is the pressure-time curve which would be expected for this rocket. The middle graph is the pressure-time curve actually recorded by a pressure transducer which responds only at low frequencies. The bottom graph is the pressure-time curve for a case in which the burning was deliberately interrupted (by blowing the end off the motor). Figure 3, top right, is the recovered, partially burned grain. The cut-out areas at the front are the expected expansions of the slots. The important feature to note is the hollowed-out shape of the grain. Obviously the propellant near the middle of the motor has burned faster than that elsewhere, contrary to the designer's expectation.

What has happened? Our meticulous designer has been introduced to the subject of acoustic resonance! Had he used a high-frequency pressure transducer he would have found that the "bumps" in his low-frequency pressure-time curve were coincident with severe pressure oscillations at quite high frequencies. Let me describe the nature of this problem.

Returning again to our burning propellant surface, let us suppose that there is a fluctuation in the incident pressure. This fluctuation in pressure may be expected to produce a fluctuation in the mass rate of production of propulsive gas. The consequences to be expected will depend on both the magnitude and the phase (that is the timing) of the mass fluctuation. The magnitude and phase of the surface response may be such that the pressure fluctuation will be weakened, or on the other hand it may be such that the pressure fluctuation will be strengthened. What I am saying is that our burning surface may be either an attenuator or an amplifier of sound.

Now, theoretical examination of the over-simplified model of the burning propellant surface described earlier indicates that we should ordinarily expect the burning surface to have the capability of amplifying sound over a rather broad frequency range, from perhaps a few hundred to a few tens of thousands of cycles per second. Let us suppose—and this is realistic—that this propellant forms a large portion of the wall of the gas cavity within a rocket. Let us also suppose that there are resonant frequencies of this gas cavity which fall within the region of acoustic amplification of the propellant. A sound wave is reflected from the surface of a propellant and is amplified in the process. Since its resonant frequency is that of the cavity, it is reflected from some other surface and returned to the surface of the propellant, where it is again amplified. One can easily see the consequence of closing this feedback loop. Every time the sound wave is reflected from the surface of the burning propellant it is increased in strength. Of course, elsewhere—at metal walls, at the nozzle, and so on—the reflections are accompanied by attenuation. The amount of this attenuation will depend quite sensitively on the design of these other surfaces, the shape of the nozzle, the thickness of the walls, and so on. We thus are confronted with the subject of the balance of gains and losses in our acoustic system. Here the problem cannot be totally localized to any one component. It is the net sum of the gains and losses of the whole system which determines the result. If the losses exceed the gains, nothing unusual will happen. If the gains exceed the losses, the system will build up in amplitude until secondary effects preclude any further gain.

It may be of interest to note that, rather commonly, sound fields of amplitudes of several hundred pounds per square inch are observed in systems operating at static pressures under 1000 pounds per square inch. The consequences of these dramatically powerful sound waves are manyfold. Heat transfer may be increased greatly, with resultant burning up of metal components. The propellant grain may be cracked or otherwise worked and damaged. Vibrations of violent type may be transmitted through the whole structure. The acoustic flow fields may dramatically change the mean burning rate of the propellant, with the result that the pressure may change to undesirable and even disastrous values.

Empirical findings relative to this phenomenon, collected over a period of more than 20 years, constitute a startling array of what may seem to be weird and apparently inconsistent results. For example, the occurrence of the phenomenon has frequently appeared to be random, and its course often intermittent. Experiments "identical for all practical purposes" have demonstrated diametrically opposed correlations. Clearly, this was a problem that baffled those observing it. Many nostrums for this disease have been discovered from time to time. The reason for their efficacy under some conditions and for their failure under others is not understood. This phenomenon has been with us as long as solid-fuel rockets have been. It is still a major pitfall in their design.

I will not dwell longer on the details of this complicated phenomenon. I want, however, to call attention to the fact that here is a phenomenon which stems from the physical chemistry of the combustion process at the surface of the propellant but which cannot be understood, either quantitatively or qualitatively, without reference to the elastic properties of the propellant in the solid form, the elastic properties of the walls of the system, the acoustic properties of the supersonic nozzle, and so on. This phenomenon is a property of the whole system. It does not occur when the propellants are studied in laboratory burners for the purpose of measuring their burning rates.

Where does a systematic examination of the phenomenon lead?

The first consequence of systematic examination, one finds, is that much of the apparent irrationality is swept away. For example, recognition that the acoustic system includes both the gas and the propellant elastomer as media provides one explanation of the observed intermittency and also draws attention to the boundary condition imposed on the solid medium by the metal case. It is most interesting to note that theory predicts, in certain cases, that variation of a few thousandths of an inch in the fit of the grain to the wall will cause a major change in the acoustic properties of the system. Here is a factor which is surely trivial in most senses but is vital to this kind of acoustic system. It appears that the apparent randomness and strangeness of many of the phenomena observed are due to failure to recognize the importance of just such trivialities.

The second consequence of systematic examination is that quite different and more definitive objectives for experimental studies become apparent. In particular, attention is focused on the acoustic-amplifying property of the burning surface. This response to a periodic pressure fluctuation can be defined by theory as a characteristic property of a propellant which should be directly measurable. Although effort has been expended for many years in the experimental characterization of propellants in terms of the properties governing their performance, this particular property has been given little attention. Now that this property of the propellant, as a component in the acoustic system represented by the solid-fuel motor, has been singled out, a number of experimental approaches to its measurement are under way. There is reason to hope that in a few years such measurements will be routine.

Thus, a major challenge for the physical chemist and his colleagues in propellant physics and chemistry is that of measuring the acoustic response of a burning propellant, understanding and controlling this ability of a solid propellant to amplify a sound wave, and reducing it to acceptable levels.

Just one more word about acoustic resonance. Theory predicts and experiment demonstrates the following relationships, other things being equal: (i) the greater the specific impulse of the propellant, the greater the amplifying capability of a burning surface; and (ii) the lower the pressure of operation of the motor, the greater the amplifying capability of a burning surface. Since higher specific impulses and lower operating pressures are the goal of the designer of our future rockets, I believe it is obvious that the problem of acoustic resonance in solid-propellant motors must be considered to have current interest.

A Philosophical Note

I would like to close by returning to a philosophic vein. It seems to me that if anything characterizes our times it is the necessity of facing the problems which arise in closely coupled systems. Systems may be broken into components which may be studied independently. Yet the system may exhibit behavior which is by no means the simple sum of the behaviors of the components. The components acting in unison produce phenomena which might not have been expected from studies of them individually. The lesson is that in our studies of the isolated components we must not overlook the vital necessity of finding and defining the properties which allow these components to couple closely with one another, to produce the behavior pattern of the system. For the servo engineer this concept has become a profession. The alert biologist senses it in the relationship between the properties of the individual molecules of deoxyribonucleic acid, ribonucleic acid, and protein and their remarkable performance in unison in the living cell, or, again, in the relationship between properties of individual cells and the performance of a multicellular functional structure—say, a brain. But is there a more dramatic demonstration than the ability of a relatively unknown individual in, say, the Congo to take a small action and thereby rock the world, disturbing the comfort, even threatening the security, of the great powers? Can we not summarize these matters, with choice of words appropriate to the particular context, by paraphrasing the vivid line of John Donne: "No man is an *Iland*, intire of it selfe . . ."?

Notes

1. In this brief discussion of the science of solid-fuel rocketry it would be quite impossible to properly credit the many contributors to our knowledge. I would be remiss, however, if I did not acknowledge my indebtedness to my colleague Dr. Robert Warren Hart, without whose close collaboration I should never have been able to discuss the subject of acoustic resonance in solid-fuel rockets.
2. I wish to thank T. Angelus of the Allegany Ballistics Laboratory for this illustration, taken from the results of his extensive studies of this phenomenon at that laboratory.

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News and Comment

The Civil Defense Debate: Neither Side Is Talking the Other's Language

As noted here last week, the debate in Congress over the Administration's Civil Defense program is shaping up as primarily one over whether the program will be worth the money that will be spent on it; this congressional debate is not likely to be very pertinent to the debate going on outside of Congress, particularly in scientific and academic circles, which is chiefly concerned with whether the whole idea of an extensive civil defense program is well-advised to begin with.

The Administration's position, at heart, is a simple one: there exists an undefinable but undeniable possibility now and for the foreseeable future that we might be subjected to a nuclear attack; therefore it would be prudent to take some precautionary measures. The opposing case, at heart, is almost equally simple: that a nuclear attack, on almost any scale, with or without civil defense, would be such an indescribable disaster that it would be folly to adopt a policy which might mildly mitigate the disaster if the price of adopting the policy is to make the disaster itself more likely to occur. A case can be made, on various grounds, that a civil defense program would increase the chance of the disaster; therefore, depending on how firmly one believes he has made this case, it would be at least questionable, and at most, outright folly, to adopt a civil defense program.

The Administration position can be attacked directly, on the grounds that it is just not worth the money it would cost. This is the heart of the debate in Congress, but is not particularly pertinent to the debate discussed here. The opponents here are not directly concerned with wasted money.

Their statements usually discuss the extent of a nuclear disaster even with shelters, but rarely as the basis for calculations of relative utility. Their point is not so much to attack the Administration's view that there are some significantly useful things that can be done now that will be valuable in the event of an attack, but to establish firmly their own basic premise on the immensity of the disaster with or without civil defense.

For some, and in fact for a great many people, the argument really ends right here with a statement of the extent of a nuclear disaster. Herman Kahn made the point before the Holifield committee that while someone could reasonably say "I prefer to be dead than Red," no one could reasonably argue that he preferred everybody to be dead than Red. If the choice came down to "Everybody Red or everybody dead," the choice had to be "Everybody Red." The choice does not have to be made anything like this unambiguous to convince someone that there is more danger involved in failing to work effectively to prevent war than in failing to prepare (with what very limited effectiveness it is possible to prepare) against the possibility that war will take place. So one can take a position against civil defense and fallout shelters, not as particularly evil things in themselves, but as a convenient symbol of the arms race.