REVIEWS

Theory of Combustion Instability in Liquid Propellant Rocket Motors, by LUIGI CROCCO and SIN-I CHENG. London: Butterworths Scientific Publications; New York: Interscience Publishers Inc.; 1956. 200 pp. 37*s*. 6*d*. or $5.25.

There are some surprises in store for those who have thought of rockets as rather superior squibs. It is perhaps no surprise that their history starts in thirteenth-century China, where they were used not only as devil-scaring fireworks but also as incendiaries. That they were used in the eighteenth century by the Indians to break up British cavalry charges appears to be substantiated, for it was from India, at the close of the eighteenth century, that Sir William Congreve and others brought the idea of the rocket as an artillery weapon. Nelson bombarded Copenhagen with rockets. Francis Scott Key watched the bombardment of Fort McHenry in 1814 from a British ship, and we suppose that rockets were used in this action because in the Star Spangled Banner, which he wrote the next morning, he refers to " the rockets' red glare ". In all of these rockets and in the short range artillery rockets used in the Second World War, solid propellants (gunpowder, cordite, etc.) were used to generate the hot gases.

The development of rockets using liquid propellants was started in 1920 by R. H. Goddard in the U.S.A. and by the Society for Space Travel in Germany in 1927. Work on liquid-propelled rockets was done at Peenemunde in Germany, in California, and at Ministry of Supply Establishments, during the war. Today liquid propellent rockets are being used for aircraft propulsion, both as a main power plant and for boost during take-off, and for long range missiles, and will be used for firing the U.S. earth satellite. Large liquid rocket motors develop thrusts of 100 000 lb and more.

The rocket motor for liquid propellants seems at first sight to be comparatively simple. The combustion chamber is a tube with an injector plate forming one end and a convergent-divergent nozzle at the other. The chamber and nozzle may be lined with refractory material or, more generally, cooled by the propellant. A large number of small holes are drilled in the injector plate, and the propellants are forced through them, either by pumps or by applying gas pressure to the fuel tanks. The pressure in the combustion chamber generally lies between 300 lb per sq. in and 600 lb per sq. in., and the pressure drop through the injector plate is of the order of 100 lb per sq. in.

The hot gases may be generated by the exothermal decomposition of a single liquid. For example a monopropellant such as hydrogen peroxide decomposes with the evolution of heat into hydrogen and steam. Alternatively two reacting liquids, one known as an oxidant and the other as fuel may be used. Oxidants commonly used are liquid oxygen and nitric acid

Fuels include alcohol, and kerosine. Factors which affect the choice of propellants include availability (or price), ease of handling, toxicity, and the performance. The performance is specified in terms of the specific impulse, that is, the thrust produced per unit flow rate of total propellant. Specific impulses vary normally from 200 to 250 lb of thrust per lb per second of propellant flow. A rocket developing a thrust of 100 000 lb therefore uses fuel at an alarming rate, between 400 and 500 lb per second. At this rate an ordinary motor car petrol tank would empty in about one fifth of a second. Large valves and pipes of high capacity are required for the propellant feed. Turbo-pumps developing several thousand horsepower may also be required. The rate of propellant flow to the injectors has to be controlled. Systems have been devised using constant injection pressure, as may be obtained with gas pressurization, or constant feed rate, as may be obtained with a displacement pump or cavitating venturi. Combustion chamber pressure may also be used to control turbo-pump speed or feed valve openings. In addition, for bipropellant systems, the mixture ratio needs to be controlled. The propellant feed system therefore tends to become somewhat complex on the larger motors. Reliability is an absolutely essential feature of such systems. In the event of loss of flame a large pool of explosive propellant mixture could rapidly build up inside the rocket with every possibility of explosion.

The hazards of starting a rocket motor are considerable. Ignition is accomplished in bipropellant systems by an igniter flare, and in mono-propellant systems generally with a catalyst. Ignition must be sure, or there is again a danger of collection of unburnt propellant which may explode. Another hazard of more subtle origin occurs because the build-up of chamber pressure in the starting phase introduces transients into the propellant feed system and into the combustion process. From these transients instabilities may develop which may end in explosions, or holes may be burnt in casings and injector plates, thus leading to the collapse of the rocket and to fires as the fuel lines are severed. Failures develop very rapidly, and the detection and prevention of the spreading of a failure is difficult because of the short total times involved (no more than 15 to 60 seconds for liquid rockets). It has been found that oscillations of pressure in the combustion chamber and propellant lines may be the precursor of failure.

Practically all of what is known about the design and behaviour of rocket motors has been found by trial and error. No one *designs* an injector plate with its multitude of small holes, they *develop* it. The high temperature of rockets (now a white rather than a red glare) makes the ordinary difficulties of experimentation in practical combustion systems even greater. Measurements are limited by these difficulties to determinations of thrust, fuel consumption, chamber and other pressures, and some temperatures. Detailed exploration of the processes of liquid jet impingement, droplet evaporation, mixing and combustion within the chamber, have hitherto been practically impossible.

Owing to the large density changes from liquid to burnt gas, simulation in the absence of combustion is unsatisfactory. The assessment of the merits of an injector plate depends on a few overall measurements interpreted in the light of the ‘ feeling ’ of the investigator. Over the extensive period of development which appears necessary, investigators grow up, get better jobs, and in this and other ways any small thread of continuity in a series of not very precise assessments is lost. This process has given us injector plates and rocket motors which work, although it has not given us any very precise idea of how they work or how to design other plates. Those groups who have spent much time and effort in rocket development have acquired know-how, but not enough knowledge to make the procurement of a new, large rocket motor anything but an expensive and protracted development process.

It is against this general background of rocket development that one must assess the monograph by Crocco and Cheng. The problem of instability in rocket motor combustion is difficult to treat analytically, but it is the most expensive unknown in rocket development. Instability in the combustion seems, at best, to increase the local heat transfer rates, which often leads to burning of injector plates or other walls, and at worst it may cause oscillations in pressure large enough to lead to explosions. In current testing practice any detectable vibration is generally the signal for a shut-down for safety. The authors have treated two kinds of instability. The first is a low frequency ‘ chugging ’ in which chamber pressure and propellant feed interact to build up oscillations (of 40 to 120 cycles per second) in chamber pressure and propellant feed rate. The second, known as ‘ screaming ’, is a high frequency oscillation (of 600 to 2000 cycles per second) which is related to the fundamental longitudinal acoustical mode in the combustion chamber with both ends closed (so that the frequency varies inversely with chamber length). The treatment is perforce confined to the linear instability of small disturbances. The basic assumptions in such a treatment are all-important, and the assumptions made by the authors about the combustion process in particular are worth noticing here.

In liquid rockets propellants are injected through the small holes in the injector plate as liquid jets. Some of the holes are drilled at an angle in order to make neighbouring jets impinge. Fuel and oxidant jets are interspersed, and the total and relative rates of injection per unit area of face of the injector plate may vary with radial distance from the axis of the combustion chamber. More fuel (relative to oxidant) is often injected near the outer wall to reduce gas temperatures at the wall. In the monograph it is assumed that the flow is radially uniform and substantially one-dimensional. It might then have been assumed that, as the propellant passes axially along the combustion chamber, it changes discontinuously from liquid to vapour and then mixes and reacts to form burnt gas. Such an assumption would have made possible an allowance for any delay in reaction due to imperfect mixing. Actually the authors prefer to assume that the liquid volume is negligible so that the chamber is filled with gas, and that immediately after the liquid evaporates it burns, the time spent in the unburnt gas phase being negligible. The time between injection and combustion of an elementary mixture is called the *time lag*. It may differ with differing propellant elements, and is made up of a portion which is insensitive to chamber pressure, this being the time for jet impingement and droplet formation, and a portion which is sensitive to variations in chamber pressure, being the time for evaporation and combustion. The relation between the rate of burning and the rate of injection of a propellant element is expressed by the value and rate of change of the combustion time lag.

The authors imagine that the propellants enter the combustion chamber as droplets of negligible total volume and, in the steady operating state, change to burnt gas. In one case they assume that the change to burnt gas of all droplets occurs simultaneously at a specified distance from the injector plate, the droplets having passed through a stationary (or re-circulating) mass of burnt gas. In this case one may assume that all droplets pass along the same path and have the same characteristics, so that their time lag is the same. Alternatively there may be a spread in time lag due to different droplets having passed to the combustion front along different paths. In other cases the ' combustion ' is assumed to be distributed along the axial length of the combustion chamber. Here again different and independent assumptions may be made about the time lag distribution. The only question which these assumptions introduce (apart from the major difficulties of determining numerical values for time lags and combustion distribution) is whether the assumption that all the gas is burnt will introduce appreciable error.

In the treatment of chugging, the frequencies are low enough to permit the assumption that the gas pressure is uniform in the combustion chamber and varies only with time. Further assumptions are that the temperature is constant and that the time lag is uniform, and the authors include an examination of the effect of variations in these assumptions. The governing equation is then reduced to a mass balance, relating the rate of generation of burnt gas to its rate of ejection through the nozzle plus its rate of accumulation in the combustion chamber. The rate of generation of burnt gas is related to the rate of injection of propellants by the time lag. The rate of ejection through the propelling nozzle, when upstream conditions are oscillatory, is found to depend on the frequency of the oscillations and the geometry of the subsonic portion of the nozzle. The solution of the resulting equation depends on the dynamics of the propellant feeding system. Some relatively simple examples are solved numerically. An interesting suggestion which is examined is the use of a servo-stabilizer in which a variable capacity of the feeding system is introduced and is suitably controlled by the chamber pressure.

The results of the analysis of chugging should be and have been of considerable value. They show the direction in which changes should be made to improve stability ; for instance, change of the feeding line length and increase of injector pressure drop both help. Of considerable importance is the interaction index n, which occurs in the assumption that the combustion rate is proportional to the nth power of the pressure. The authors argue that n, which covers the pressure dependence of the evaporative as well as of the combustion process, will be of the order unity and larger and show that increase of n has a destabilizing effect.

In the range of frequencies of screaming, the wavelength of standing oscillations becomes comparable to the length of the combustion chamber. Local pressure variations must therefore be taken into account, so that the spatial distribution of combustion and pressure becomes important as well as the combustion time lag and the time variation of pressure. The authors consider a number of cases, starting with the simplest in which the time lag is uniform and combustion is concentrated at one axial position.

Of major interest is the determination of the boundary conditions at the nozzle end of the combustion chamber. In a one-dimensional analysis the authors show that the convergent-divergent nozzle behaves more like a closed end than an open end to the combustion chamber. The reflections are weaker than, and displaced in phase relative to, those at a simple closed end. The authors show that increasing the length of the subsonic portion of the nozzle has a stabilizing effect. The shape of the converging portion also has an effect, the best shape suggested being that which produces a velocity distribution linear with the axial length.

The instability due to transverse (or swashing) oscillations is mentioned only briefly. This is unfortunate, since it now appears that this form of oscillation is at least as important as the others described.

One major critical question which may be raised is whether such a specialized book is timely. The structure of ideas and the mathematical models underlying the analysis rest on too weak a foundation of experiment for the volume to be in any sense definitive. Admittedly, one of the objects of Agardographs (that is, monographs sponsored by the Advisory Group for Aeronautical Research and Development, attached to NATO), of which this book is one, is to present current thought and so to stimulate experiment and research. On reading this book the rocket researcher might well be stimulated to answer experimentally such questions as, what is the value of the interaction index, what are the neutral stability points, and what is the effect of injector plate design on these and other factors? But could not the authors' ideas have been communicated better in the customary medium of papers in journals, and their reproduction in book form postponed until theories are better established and more solidly supported by experimental results?

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