Aerospace Science and Technology, 1998, no. 6, 359–367

A novel kind of solid rocket propellant

Roger E. Lo

Rocket Technology at the Aerospace Institute (ILR), Berlin University of Technology,
March Str. 12, D-10587 Berlin, Germany

(Received 11 March 1998, accepted 18 May 1998)

Lo R. E., *Aerospace Science and Technology,* 1998, no. 6, 359–367.

Abstract

Cryogenic Solid Propellants (CSPs) combine the simplicity of conventional solid propulsion with the high performance of liquid propulsion. By introducing materials that require cooling for remaining solid, CSPs offer an almost unlimited choice of propellant constituents that might be selected with respect to specific impulse, density or environmental protection. The prize to be paid for these advantages is the necessity of constant cooling and the requirement of special design features that provide combustion control by moving from deflagration to hybrid-like boundary layer combustion. This is achieved by building the solid propellant grains out of macroscopic elements rather than using the quasi homogeneous mixture of conventional composites. The elements may be coated, providing protection and support. Different elements may be designed for individual tasks and serve as modules for ignition, sustained combustion, gas generation, combustion efficiency enhancement, etc. Modular dissected grains offer many new ways of interaction inside the combustion chamber and new degrees of freedom for the designer of such "multiple internal hybrid grains".

At a preliminary level, a study finished in Germany 1997 demonstrated large payload gains when the US Space Shuttle and the ARIANE 5 boosters were replaced by CSP-boosters. A very preliminary cost analysis [5] resulted in development costs in the usual magnitude (but not in higher ones). Costs of operation were identified as crucial, but not established.

Some experimental work in Germany is scheduled to begin in 1998. However, almost all details in this article (and many more that were not mentioned - most prominent cost analyses of CSP-development and operations) wait for deeper analysis and verification. Actually, a whole new world of chemical propulsion awaits exploration. The topic can be looked up and discussed at the web site of the Advanced Propulsion Workshop of the International Academy of Astronautics. The author would be pleased to provide the necessary access data. © Elsevier, Paris

rocket propulsion / high energy density matter / cryogenic solids / solid propellants / hybrid propellants

Zusammenfassung

Eine neue Klasse fester Raketentreibstoffe. Kryogene Festtreibstoffe (CSPs) vereinen die Unkompliziertheit konventioneller Feststoffantriebe mit der hohen Leistung von Flüssigkeitsantrieben. Durch die Verwendung von Stoffen, die gekühlt werden müssen um fest zu bleiben, bieten CSPs eine fast unbegrenzte Auswahl verwendbarer Treibstoffbestandteile, die nach spezifischem Imputs, Dichte oder Umweltschutz ausgesucht werden können. Der Preis für diese Vorteile ist mit der Notwendigkeit ständiger Kühlung zu zahlen und damit, dass Entwurfscharakteristika erforderlich werden, welche eine Kontrolle der Verbrennung dadurch ermöglichen, dass von der Deflagration zu einer Grenzschichtverbrennung wie in Hybriden gewechselt wird. Dies wird durch den Aufbau der Feststofftreibsätze aus makroskopischen Elementen erreicht, die an die Stelle der quasihomogenen Mischung konventioneller Komposittreibstoffe treten. Die Elemente können zum Schutz oder zur mechanischen Unterstützung ummantelt werden. Verschiedene Elemente können für verschiedene Aufgaben ausgelegt werden und als Module zur Zündung, Unterstützung von Abbrand und Verbrennungsgüte, Gaserzeugung, etc. dienen. Modulare, fragmentierte Treibsätze bieten zahlreiche neue Möglichkeiten der Wechselwirkung in der Brennkammer und neue Freiheitsgrade für den Konstrukteur solcher "multipler internen Hybridantriebe".

Eine 1997 in Deutschland beendete Studie erbrachte als vorläufiges Ergebnis den Nachweis, dass grosse Nutzlaststeigerungen bei US-Space Shuttle und ARIANE 5 zu erwarten wären, wenn deren Feststoffbooster durch CSP-Booster ersetzt würden. Eine sehr vorläufige Kostenanalyse ergab Entwicklungskosten in der üblichen Grössenordnung (aber nicht mehr !). Die Betriebskosten wurden als kritisch erkannt, aber nicht ermittelt.

Einige experimentelle Arbeiten sollen 1998 in Deutschland begonnen werden. Fast alle in diesem Artikel erwähnten Details (und viele andere, die nicht erwähnt wurden - darunter an prominenter Stelle Kostenanalysen für CSP-Entwicklung und Betrieb) harren auf tiefere Analysen und Bestätigung. Im Prinzip wartet hier eine völlig neue Welt chemischer Antriebe auf ihre Erforschung. Das Thema kann im INTERNET auf den Seiten des "Advanced Propulsion Workshop" der Internationalen Astronautischen Akademie angesehen und diskutiert werden. Der Autor vermittelt gerne die notwendigen Zugangsdaten.

Raketenantriebe / Superhochenergetische Treibstoffe / Kryogene Feststoffe / Festtreibstoffe / Hybridtreibstoffe

1. Introduction

Conventional solid rocket propellants are divided into Double Base Propellants, using a solution of nitro cellulose in nitro glycerol (both are explosives) and Composite Propellants usually with Ammonium Perchlorate as typical oxidiser and hydrocarbon binder and metal powders (Aluminium) as fuels. Some advanced formulations use combinations of both propellant types and some more or less exotic ingredients. Solid propellants are used in large and small motors in a wide variety of applications. Their simplicity warrants a high degree of reliability and the cost of development of large solid motors is much lower than with their liquid counterparts. However, neglecting minor variations, they all have in common that specific impulses are low compared with cryogenic liquid propellants and production requires hazardous operations such as casting, mixing and curing.

Research done since 1995 at ILR suggests that solid propellant formulations need not be restricted to materials that are solid only at ambient temperature. Defining Cryogenic Solid Propellants (CSPs) as propellants using frozen liquids or gases, most of such formulations will compare favourably with conventional ones in any of the above areas. Preliminary investigations were sponsored by the German Aerospace Research Establishment (DLR, formerly DARA).

In an expert opinion by the European Space Agency ESA in 1997 and also as a result of the Advanced Propulsion Workshop of the International Academy of Astronautics (IAA) at El Segundo, Calf., January 1998, the concept was considered as having the potential of revolutionising solid rocket propulsion.

The purpose of this article is to describe this concept in terms of its differences in comparison with more conventional types of chemical propulsion. Due to the generic level chosen, details of individual examples were not the subject of this article. These will have to wait for future work.

2. The CSP concept

Cryogenic Solid Rocket Motors use cryogenic solids as propellants, such as solid hydrogen ("SH_2" where S stands for solid) and oxygen ("SOX"). Actually, any single propellant or mixture of propellants of which at least one requires cooling to remain solid, constitutes a cryogenic solid propellant [1]. Thus, any conceivable chemical propellant combination, liquid or other, be it a mono-, bi-, or tripropellant, can be transformed into a CSP for use in a Cryogenic Solid Rocket Motor. As a result, CSPs share all advantages of solid propellants except their storability and all disadvantages except their limitation to constituents that are solid at ambient temperature. The consequences are evident: this novel kind of solid rocket propulsion covers the whole range of chemical propulsion in terms of propellant composition, performance, density and other system parameters.

CSP grains are stored in the combustion chamber similar to conventional solid propellant grains. Compared with conventional solids, the concept is attractive because the propellant constituents can be chosen for high Isp and/or for much more environmentally benign exhaust gases than those of

[1] In this context, "propellant" is used as generic designation for fuel and/or oxidiser.

conventional solid rockets. In this respect, CSP propulsion is neither better nor worse than liquid propulsion.

Considering CSP problems, some of the items of particular concern that will have to be proved are the following:

- Compared with liquid propellant combinations the Isp of CSPs could be much lower due to lower energy content at a given mixture ratio (subcooling and missing heat of liquefaction) and due to the restriction to chamber pressures lower than those attainable with liquid combustion.
- The mechanical properties of propellant constituents could be a great obstacle in terms of strength, case bonding and other requirements
- Cryo-technology dictates a set of special requirements (e.g. cooling and heat insulation in all phases of operation) that might spoil the favourable system parameters (e.g. thrust / weight ratio) and operational characteristics (storage, transportation) of conventional solids in an unacceptable way.
- Cooling and heat insulation requirements could also become prohibitive in terms of energy consumption and other parameters not normally of concern in rocket operations.
- It might be impossible to design suitable grain shapes (for thrust vs. time tailoring), because it is the disadvantages of solids (no throttling) and hybrids (no real mixture ratio control) that combine, rather than their advantages.
- It is not at all clear, whether CSPs can be expected to exhibit quasi steady state combustion. Given the large spectrum of possible propellant choices and geometrical designs, this is not a question to be answered in a general way.
- Problems might arise under off-design conditions (e.g. breakdown of the cooling system) that are serious enough for rendering the idea unfeasible.

At present most of these concerns have yet to find a final solution. However, so far none was identified for which no such solution is thinkable.

3. Dissected propellant grains with variable mixedness

The author has been thinking about cryogenic solids since quite a while, actually since 1967, see [2]. The prototype of all cryogenic solid propellants would of course be SOX/SH_2. One major objection against SH_2 combustion with SOX had always been the predicted occurrence of intolerably unstable combustion up to DDT (the transition of deflagration to detonation). Therefore, as a central hypothesis of the CSP concept, the author suggested in 1994 that the physical separation of frozen propellant elements could effectively prevent such problems. Example configurations are axial SOX-rods in a SH_2 matrix, or alternating disks of SOX and SH_2 with a central combustion channel of arbitrary shape. The rod/matrix solution and the designation "Cryogenic Solid Motor" were mentioned in October 1994 in a diploma thesis with different scientific objectives [5]. Of course, some cryogenic propellant combinations could exist that would burn properly even when the constituents were intimately mixed. However, in general one has to assume that CSP grains have to be dissected into macroscopic elements of oxidiser and fuel elements.

In doing so, one obtains an additional degree of freedom vis-à-vis conventional solids. Consider a cylindrical motor case with a sandwich type grain. If all the oxidiser were present as one element upstream of one single fuel element, the resulting "solid propellant" would not have much reason to ignite and keep burning. If the oxidiser were molten and evaporated by some appropriate means (e.g. a hot gas generator located up-stream), the situation would resemble a hybrid motor without external liquid storage and therefore the motor – as far as the combustion situation is concerned – can be designated as "internal hybrid". Increasing the number of alternating disks transforms the combustion situation into a "multiple internal hybrid", with combustion occurring in a boundary layer fed by alternating sources of oxidiser and fuel vapours. Combustion efficiency can be expected to increase with the number of sources (multiple merging boundary layers). Whatever the practical upper limit for thin slices may be, the danger of explosions may reappear then or even earlier.

There are many different ways of designing dissected grains. Consider for instance end-burning cylindrical grains with concentric layers of oxidiser and fuel, or axial star shaped combustion channels formed by wedge shaped propellant elements. Obviously some parameter called "mixedness" could easily be defined that characterises the various geometries. One of many possible definitions is the following:

$$m = A_{O/F}/(V_{gr} \cdot D_{cg})$$

where

$A_{O/F}$ = interface area between oxidiser and fuel (the size of touching surfaces, as one obvious parameter of influence to reactivity, regardless of the presence or absence of a coating)

V_{gr} = total propellant volume (grain volume, not chamber volume)

D_{cg} = average distance between the centres of mass of oxidiser and fuel elements.

Mixedness is thus defined as *O*/*F* interface area per unit propellant volume divided by average distance between *O* and *F* elements. Building the same grain geometry with different mixedness by using elements of different size and/or shape provides a means of influencing the regression rate within certain limits. This is a degree of freedom absent in ordinary solid rocket motors. Mixedness serves well for comparing CSPs among each other. However, it does not make a lot of sense to compare individual CSPs with conventional solids.

As a simple example, consider a CSP-Booster of STS-SRB size, using SOX/RP-1 as solids in a disk-stack arrangement. With a total of about 70 slices it would have an interface area of about 400 m^2 and mixedness would roughly be 2 per square meter. This figure increases by a factor of about 4 whenever the number of slices is doubled.

A conventional composite, on the other hand, with 80 % AP ($\rho = 1.95$ g/ml) of 200 μm particle diameter and 20 % HTPB ($\rho = 0.92$ g/ml) contains about 150 billion particles per cubic meter with an Average (cubic lattice) distance of about 0.2 mm. The interface area is about 20 000 m^2 per m^3 and the resulting mixedness is 100 million per square meter.

4. Modular dissected propellant grains

The striking difference between the mixedness of conventional solids and CSPs provides the latter with an opportunity not available in the case of conventional solids: the elements can be enclosed in a macroscopic envelope or coating that acts as protection and support. While coating or encapsulation are certainly not necessary in most conventional solid propellants, this opportunity takes care – at least in some CSPs – of several grave concerns:

- During storage, envelopes provide chemical separation between individual propellant elements. The coating material – be it metallic or non-metallic – has to be sufficiently non-reactive vis-à-vis the propellants. This property defines and limits the storability of the elements. CSP elements based on storable liquids (like NTO/UDMH, NTO/RP-1, H_2O_2/N_2H_4, etc.) could perhaps be stored at ambient temperature in the same manner as the liquids themselves, even though some of these react hypergolic when in contact.
- More robust envelopes – or rather shrouds - provide mechanical support. The lower and outside parts of propellant elements of any shape can be used for support. Areas in contact with the outer chamber wall could be case-bonded and/or mechanically linked with the wall, e.g. by thin wires or struts between wall and lower base of individual elements, both designed taking into consideration the progressing destruction by combustion. The mechanical strength required of individual frozen propellant elements is thus reduced to supporting their own weight if any, rather than that of all upper elements.
- Envelopes are also convenient for attaching cooling equipment to the elements. It is easy to show that cooling pipes (most conveniently entering and leaving through the nozzle) could be attached to all inside surfaces of encasements of almost any shape.
- Envelopes provide containment when the refrigeration fails. Of course, space must be provided for thermal expansion, overflow and save venting. The same piping could be used for fill-drain purposes.
- It is obvious, that the rate of consumption of the coatings or encasement walls must be carefully matched with the propellant regression rate. Fortunately, in boundary layer combustion, prominent features have higher than average regression rates, while concave features have lower ones. At higher degrees of mixedness, modular dissected grains have also considerable advantages in comparison to hybrids, where one component remains liquid. As was already pointed out above, multiple internal hybrid combustion offers an additional degree of freedom and is almost certain to provide higher regression rates and better combustion efficiencies.

It is not unthinkable, that some types of cryo propellant grains, as composites of shrouded elements, could be assembled at room temperature. Of course, the feasibility of all these concepts remains to be demonstrated.

In many cases, high combustion rates are advantageous in rocket motors. The hybrid combustion situation described in the previous section is notorious for low regression rates. Dissected grains are certain to show increasing regression rates with increasing mixedness. For a given shape it will depend on the chemical composition of the elements and their envelopes. Metallic coatings (foils) used in grains of sufficiently high mixedness (e.g. thinly sliced sandwich propellants) could have the same enhancing effect as in classical grains with metal wire embedding. A well known means for increasing regression rate in hybrids is the addition of oxidiser into the fuel grain, see for example [4]. Still another way of enhancing regression rate is the interspersed addition of elements capable of burning in a self sustained way (gas generator elements). An example concerning an end-burning grain will be shown further below.

In general, the behaviour in terms of combustion rate and stability of oxidiser/fuel mixtures (as mixtures are defined in conventional composites) can be depicted as shown in the generic diagram in *figure 1*. For any chosen propellant combination there will be a line similar to the arbitrary example in this figure. However, it would have to be redrawn for any change concerning the presence of further constituents, or changes of pressure and other parameters influencing combustion. Used as elements

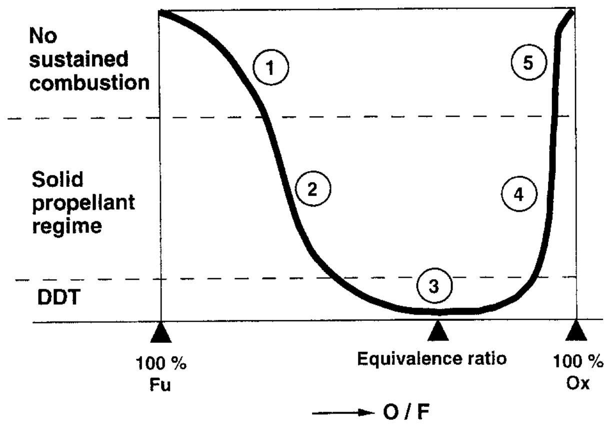

Figure 1. Generic combustibility and combustion stability regions over mixture ratio.

in a multiple internal hybrid solid rocket motor with dissected grains, propellant elements would acquire enhanced regression rates vis-à-vis elements made out of 100 % oxidiser or fuel, even if the mixtures were too lean for sustained combustion (line segments 1 and 5). Adding more fuel to oxidiser rich mixtures and vice versa yields genuine solid propellants that keep burning after ignition (line segments 2 and 4). There might or might not be one or several areas with combustion too unstable for use, including "DDT", the "deflagration-detonation-transition" as the worst case. It was arbitrarily assumed to be located around the chemical equivalence ratio: line segment 3. It should be understood, that *figure 1* serves the sole purpose of defining these regimes of principal interest for modular dissected propellants. Individual cases (monopropellants in particular) could show quite different behaviour, not fitting into this scheme. One or more of these regions might be missing altogether. The abscissa was therefore left without scale.

Given the different behaviour of mixtures in the regions defined in the diagram, such elements could be used as modules that serve different functions, such as:

- ignition
- sustaining combustion
- generation of fuel- or oxidiser-rich gases
- cross flows for combustion efficiency and/or regression rate enhancement.

It goes without saying that different modules in one propellant grain (i.e. in one particular type of motor), while deliberately using different mixture ratios between (and including) 100 % fuel and oxidiser, need not be restricted to one propellant combination. Thus, conventional propellant modules might be used along with CSPs of different composition, provided that they all can share the same temperature environment. In *figure 2* is shown a solid rocket motor with modular dissected grain in conocyl shape (all dimensions, shapes, ratios and number of elements are examples without significance). As indicated, the intermediate elements might be pure oxidiser and fuel. However, the element at the upstream end might be an igniter module which also keeps burning as long as the adjacent element needs energy for melting and evaporation. It might use a suitable conventional propellant or, if possible, a mixture of the main CS-propellant combination in a mixture ratio of self sustained combustion. At the other end of the grain, near the nozzle, there could be regions where the hybrid analogy is not valid. As a consequence, a mixture ratio with self sustained burning is again required, such as a fuel rich gasgenerator element. With suitable dimensions and shape, the radial mass flow could act like the jets in a mixing chamber and as film coolant for the nozzle.

Finally it should be noted that the overall mixture ratio of the constituents present in the grain and combustion chamber ought to add up to some general average value as desired by Isp considerations.

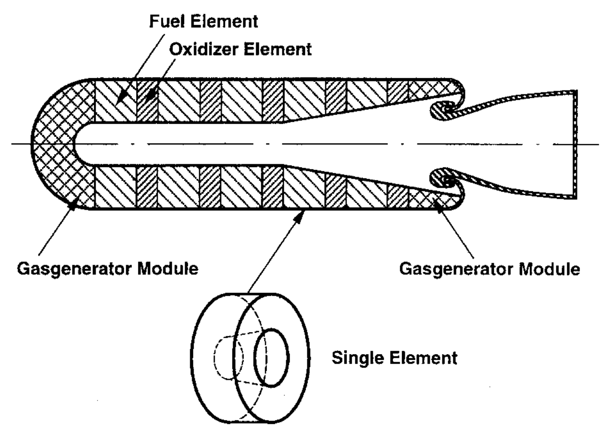

Figure 2. Solid rocket motor using a modular CSP grain in disk-stack design.

5. Comparing CSPs with Conventional Composites

Particular problem areas that require further research and attention can best be identified by comparing the advantages and disadvantages of the two types of solids. Talking about a class of chemical propellants that comprise virtually all possible combinations of materials suitable for use as rocket propellants, it is rather difficult to formulate statements of general validity. The following examples are meant as cases in point – they will all have to be verified and their details were not the subject of this article. Counter examples will be easy to find in most cases.

5.1. Advantages of CSPs

- Isp values are as high as any chemical propellant combination can go (minus latent heats of melting and temperature difference).

- There exist many combinations that are as environmentally benign as chemical propellants can be (e.g. SOX/SH_2, SOX/RP1, SOX/Polyethylene).
- There exist many combinations with high volume specific Isp, i.e. with high average propellant density and high Isp (e.g. $SOX/(SH_2+Al)$, SOX/(RP1 + Al), NTO/(RP1 + Mg) and many others). At design conditions, there is no slurry storage problem.
- Much simpler propellant chemistry. All CSP combinations, that could also be used in liquid propulsion, inherit this benefit. Chemical considerations play the same minor role as in liquid propulsion (the role of additives other than energisers is negligible).
- Much simpler manufacturing in terms of chemical process engineering. Apart from gas-generator elements, which must be considered as conventional solid propellants or as hybrid grains with oxidiser addition, the dissected elements of multiple internal hybrid motors use simple, uniform chemical compounds without need for additives, stabilisers etc. In most cases, propellant chemistry will be reduced to questions of compatibility with the coating material.
- Lower reactivity during storage. Assuming storage under frozen conditions, chemical reactivity is clearly lower than in the liquid state due to reduced temperature and absence of convection. This holds for interactions between oxidiser and fuel in areas of direct contact and for reactions with coating materials. It is also true for the propellants themselves: by deep freezing, some sensitive propellants could perhaps become sufficiently well behaved for being used (e.g.: H_2O_2 or many "exotic" ingredients considered for conventional solids, as well as Ozone, O_2/O_3 and many more).
- Boundary layer (i.e. diffusion flame) combustion as in hybrids. Therefore no deflagration, no shock sensitivity. Benign reaction to cracks (as long as mechanical integrity is preserved).

5.2. Disadvantages of CSPs

- In many cases, permanent cooling will be required between manufacture and use. Storability will be at least as limited as with cryogenic liquids.
- Lack of experience in process-engineering for production (grain design and manufacturing, grain fastening and support, inner and outer thermal insulation), storage (energy consumption) and transportation (sensitivity, safety).
- Incomplete knowledge of the properties of cryogenic solids (thermal and thermodynamic, mechanical, physico-chemical, chemical properties and many more).
- Extremely important: almost total lack of knowledge about operational properties and behaviour (regression rate, pressure gradient, stability, ignition, transients and many more.). Some research about combustion of cryogenic solids in hybrid rockets was published by USAF-Phillips Lab, Edwards AFB [1] as the only experimental experience with frozen materials in rocket combustion.

6. Feasibility of CSPs

A feasibility study sponsored by the German Space Agency (formerly DARA, now DLR), limited to the SOX/SH_2 case was finished in 1997 [6]. Considering large CSP-motors (boosters), it revealed the absence of any major show-stoppers. Some of the results are presented in the following paragraphs, along with a more general analysis of CSP feasibility.

6.1. Theoretical performance

Isp of SOX/SH_2 is less than 1 % below LOX/LH_2. As *figure 3* shows, even sub-cooling does not make much difference.

6.2. Cooling and heat insulation requirements

These are of utmost importance for the concept. Requirements can be divided into three phases: during launch preparation, immediately before launch and after launch.

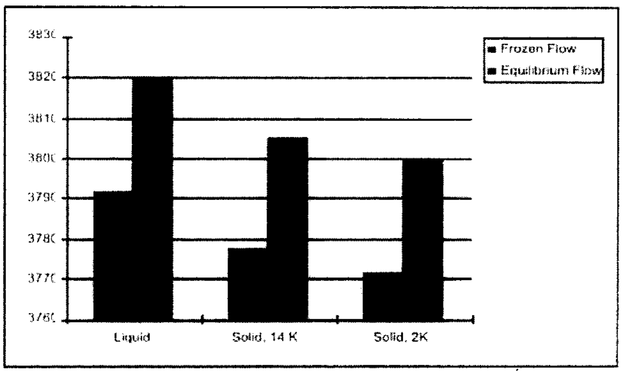

Figure 3. Mass specific impulse [m/sec] of O_2/H_2 propellants at optimum mixture ratio, standard 68:1 expansion [6].

Prior to launch, the best way of keeping a solid propellant grain cold is to wrap the motor in heat tight layers of insulation and cooling it from the inside, i.e. through the nozzle (internal burners only). An operational scenario established in the course of the DARA study assumed booster production close to the launch site. Three obvious requirements on cooling are:

- Assured availability under stationary and mobile conditions.

8

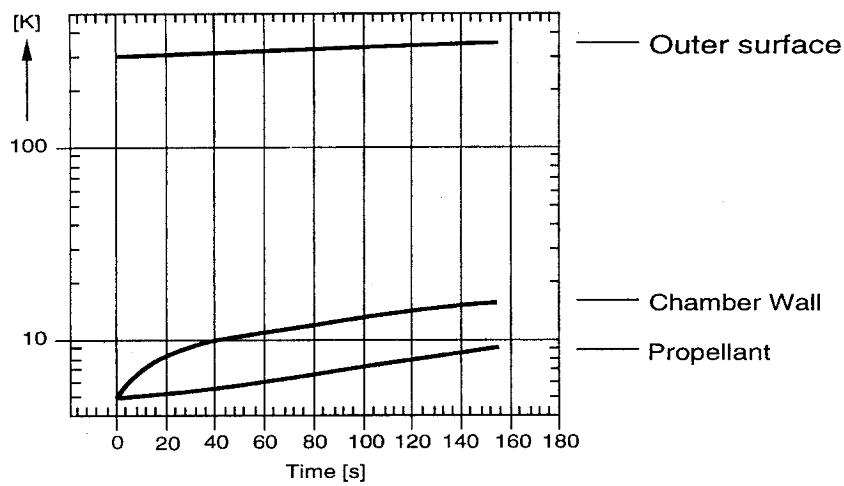

Figure 4. Temperature-time history of a CSP-booster during ascent [6].

- Spatial compatibility with the launcher and launch pad geometry.
- Ease of application including connect/disconnect operations.

Immediately before launch, the cooling equipment will be removed. External insulation is thus reduced to the flightworthy part of it. In this phase, any condensation on external and internal surfaces must be kept below some tolerable limit.

Up to here, considerable differences can be expected for different cryo propellants. However, in the third phase, during ascent, degree and duration of aerodynamic heating will be independent of the interior conditions. A preliminary result was obtained for the temperature caused by the aerodynamic heat flow during the ascent of an ARIANE 5 CSP Booster during the DARA study. The insulation used was identical to the one of the STS-External Tank (see *figure 4*). Under the special conditions assumed in this study, the average propellant temperature would never have reached the melting temperature of Hydrogen (14 K) or Oxygen (54.4 K) during the time of booster operation (2 minutes). However, assuming that the propellant surface attains chamber wall temperature, a layer of Oxygen of appropriate diameter would have had to be placed there in order to prevent surface melting. For reasons of mixture ratio control, this solution lends itself for end-burning grains (''Cigarette burners'') only. Radial burners with SH_2 in contact with the chamber wall would need more insulation. More accurate solutions, especially for longer thrust duration, remain to be designed.

End-burners require extremely efficient internal heat protection for the chamber wall. To a lesser degree, this is also true for radial burners. In addition, the grain must be protected against heat conduction along the wall.

6.3. Suitable grain shapes: radial burners

Today the typical high-low thrust over time profile required for booster missions is achieved with variations of so-called ''Finocyl'' grains (e.g. STS-SRB or ARIANE 5 CSB). A many pointed internal star at the upstream end provides a large surface for high initial thrust. Sustained thrust at a lower level is achieved by cylindrical and/or conical segments downstream of the star. It should not pose any problems to build radial burning CSPs of the type shown in *figure 2*, that have elements with proper internal star surfaces at their upstream end. Oxidiser/fuel distribution could be accomplished in several ways:

- By an equal number of alternating wedges of oxidiser and fuel satisfying the condition that the ratio of the products of free surface area times individual regression rate equals the desired mixture ratio. Unfortunately, the arbitrary example shown in *Figure 5* is not likely to be

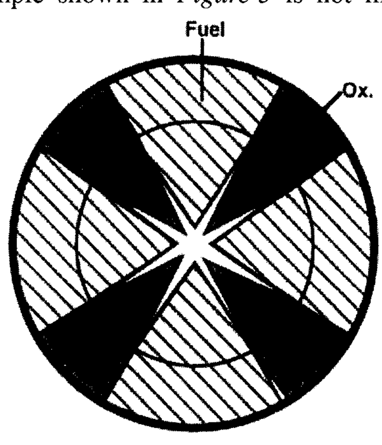

Figure 5. CSP internal star burner.

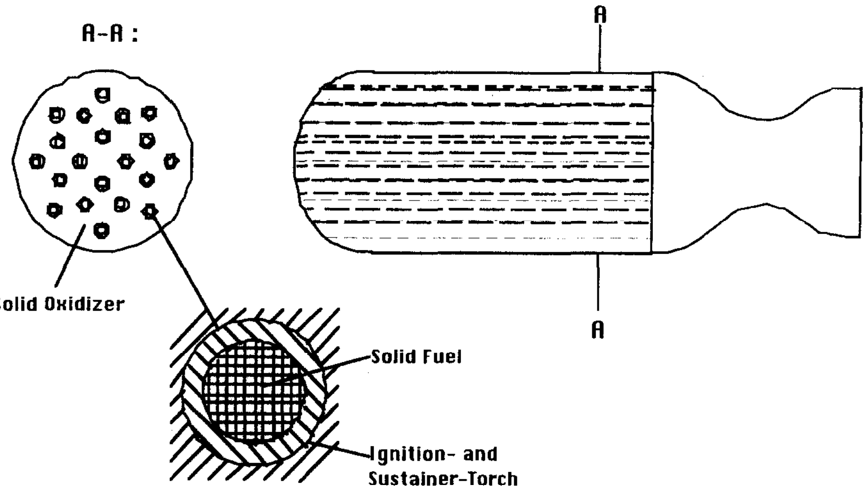

Figure 6. Schematic representation of an end-burning CSP grain [3].

very characteristic in terms of proportions, wedge numbers and degree of filling. As in many other modular dissected grains, the two kinds of elements would have to be separated by a consumable foil. In this case it must be capable of preventing non-boundary layer combustion in the groove points. This arrangement will share the problem of shifting mixture ratios with conventional hybrids.

- By a sequence of modules, beginning with a 1.) gasgenerator (as in *figure 2*) which serves as igniter and sustainer for the evaporation of the following 2.) oxidiser internal star module that in turn provides the reactant for the subsequent 3.) fuel internal star module. Of course, modules 2 and 3 can be as short as required by regression rate and combustion efficiency requirements and repeated as many times as necessary for attaining and keeping the desired thrust level before the star points meet the wall.
- In all above cases, deviation for all or some of the modules from 100 % oxidiser or fuel into the region of enhanced regression or self sustained burning could be used if required. If module 2.) in the previous example was a self sustained oxidiser gas generator, element 1.) would only be needed for ignition.

6.4. Suitable grain shapes: end-burners

End-burners offer a very high degree of chamber filling. However, most experts believe that they are very problematic in terms of chamber wall protection to the point that they cannot be used with current technology. Of course, ablative thermal insulation is a possibility, but adds to the reduction of Isp by non-propellant materials. Two examples of advanced applications are the low temperature hydrogen gas generator (e.g. for subsequent ram combustion) or the self consuming nozzle-less rocket. Here it is only intended to demonstrate the applicability of the CSP concept to this kind of solid rocket grain.

Figure 6 shows a typical rod-and-matrix design (as before: all details are arbitrary and restricted to CSP essentials). The over-all area ratio defines the mixture ratio. It remains constant as long as the surface remains in constant shape. Higher levels of total thrust could be provided with conical or other surface shapes. Variation of diameter and number of rods provides regression rate manipulation, as does the optional coating with the same or another propellant combination in a mixture ratio that provides self sustained burning. Problems of co-ordinating regression velocities aside, such coatings would provide ignition augmentation to the separated main propellant combination and act as a combustion augmenting sustainer torch for the rest of the time.

One alternative that is always to be considered when thinking about CSPs is the old fashioned quasi homogeneous mixture, see *figure 7*. There may be many examples that do not exclude this choice. The

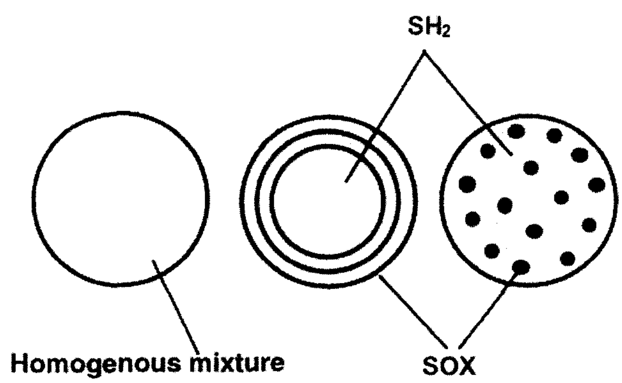

Figure 7. Alternative end burner configurations [6].

other example in *figure 7* is the concentric shell arrangement mentioned above, that provides special heat protection for the frozen Hydrogen.

References

[1] DeRose M., Pfeil K., Carrick P., Larson C., Tube Burner Studies of Cryogenic Solid Combustion, Phillipps Lab, Edwards AFB, AIAA-97-3076

[2] Lo R.E., Technical Feasibility of Chemical Propulsion Systems with very high Performance, Proceedings of the XVIIIth Astronautical Congress, Belgrade, 25–29.9.1967, pp. 121-132

[3] Lo R.E., Modulare Feststoffraketentreibsätze (Modular Rocket Propellant Grains), German Patent Application No. 197 56 794.0, Dec. 19, 1997

[4] Lo R.E., LaBlonde Ch., Wirkungen der Festoxydatorbeimengung zu Lithergolbrennstoffen, Teil I: Das System FLOX/NH4NO3/Kohlenwasserstoff (Effects of Solid Oxidiser Addition to Hybrid Fuels, Part I: The System FLOX/NH_4NO_3/Hydrocarbon), DLR/USAF; Report BMBW-FB W 7047, August 1970 (in German)

[5] Voslamber B., Parametrische Analyse eines Ultrahochdruck-Kryofeststofftriebwerks (Parametric Analysis of a Cryo Solid Motor With Ultrahigh Chamber Pressure), diploma thesis in rocket technology, Aerospace Institute, Berlin University of Technology, Oct. 1994 (in German)

[6] Voslamber B., Voslamber M. and Lo R.E., Machbarkeitsstudie kryogene Feststoffbooster (Feasibility Study of Cryogenic Solid Boosters), German Space Agency DARA, Project 50TT 9631, Final report 2/1997 (in German)