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AN EXAMPLE OF SUCCESSFUL INTERNATIONAL COOPERATION IN ROCKET MOTOR TECHNOLOGY

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ABSTRACT

The history of over 25 years of cooperation between Pratt & Whitney, San Jose, CA, USA and Snecma Moteurs, Le Haillan, France in solid rocket motor and, in one case, liquid rocket engine technology is presented. Cooperative efforts resulted in achievements that likely would not have been realized individually. The combination of resources and technologies resulted in synergistic benefits and advancement of the state of the art in rocket motors and components.

Discussions begun between the two companies in the early 1970's led to the first cooperative project, demonstration of an advanced apogee motor nozzle, during the mid 1970's. Shortly thereafter advanced carbon-carbon (C-C) throat materials from Snecma were comparatively tested with other materials in a P&W program funded by the USAF. Use of Snecma throat materials in CSD Tomahawk boosters followed.

Advanced space motors were jointly demonstrated in company-funded joint programs in the late 1970's and early 1980's: an advanced space motor with an extendible exit cone and an all-composite advanced space motor that included a composite chamber polar adapter. Eight integral-throat entrances (ITEs) of 4D and 6D construction were tested by P&W for Snecma in 1982. Other joint programs in the 1980's included test firing of a "membrane" C-C exit cone, and integral throat and exit cone (ITEC) nozzle incorporating NOVOLTEX® SEPCARB® material. A variation of this same material was demonstrated as a chamber aft polar boss in motor firings that included demonstration of composite material hot gas valve thrust vector control (TVC).

In the 1990's a supersonic splitline flexseal nozzle was successfully demonstrated by the two companies as part of a US Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program effort. Also in the mid-1990s the NOVOLTEX® SEPCARB® material, so successful in solid rocket motor application, was successfully applied to a liquid engine nozzle extension. The first cooperative effort for the new millennium, a scale-up of the supersonic splitline flexseal nozzle, was begun in 2001.

Key details of the above numerous cooperative successes are presented.

INTRODUCTION

Discussion of cooperation began in the early 1970's when the part of Snecma Moteurs now involved in solid rocket motor (SRM) technology was known as Société Européenne de Propulsion (SEP), and the part of Pratt & Whitney now involved, Chemical Systems Division (CSD), was United Technology Center. Cooperation made sense because of natural synergy between the two companies. Although both had excellent overall SRM design and analysis capability, CSD primarily produced SRM propellants and propellant grains while purchasing inert components, whereas SEP primarily produced inert SRM components. Both had a strong record of innovation in SRM technology, particularly in the application of advanced materials.

COOPERATIVE EFFORTS

Ultra-simple Carbon-Carbon Nozzle Demonstration. Discussions in the early 1970's led to the first joint project, test firing of an "ultra-simple" C-C nozzle in 1977.[1] The nozzle (figures 1 and 2) was composed of an SEP 4D C-C ITE threaded to an SEP 2D involute construction C-C exit cone with a carbon phenolic insulator between the ITE and the steel nozzle flange. The nose tip-to-exit plane flow path was thus all C-C. SEP contributed the nozzle and CSD the motor and test. To minimize expenses an existing CSD nozzle design for the selected test motor was modified so that the exit cone contour matched existing SEP tooling. The successful test of this nozzle established simple C-C nozzle designs were ready for application to space motors to reduce weight and envelope and to better maintain the internal aerodynamic profile.

4D C-C ITE Evaluation. Also during the late 1970's an SEP 4D C-C ITE purchased by CSD was test fired to compare performance to ITEs of other constructions. The results

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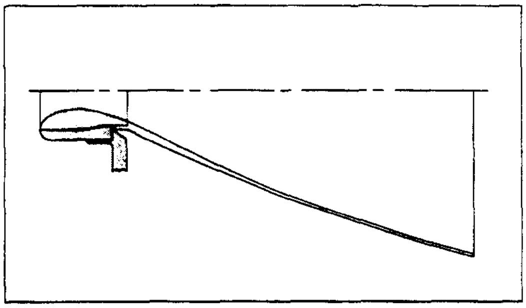


Figure 1. Ultra-simple Nozzle Design

Figure 2. Ultra-simple Nozzle

established performance was comparable or superior to that of more expensive materials.

Advanced Space Motor Demonstration. In the 1978 and 1979 period the two companies successfully accomplished an ambitious IR&D project to demonstrate several advanced technologies combined into a demonstration motor (figure 3).[2, 3] The following advanced components were incorporated:

- An SEP-designed and manufactured lightweight Kevlar® filament-wound chamber with a carbon-epoxy filament-wound skirt and SEP's silica-filled EPDM insulation.
- CSD's high performance 90% solids, 20% aluminum, 12% HMX propellant cast in a head-end web grain configuration into the SEP chamber at CSD. This was the first application of the high-volumetric-loading head-end web grain design to a filament-wound chamber. Chamber pressure was measured by drilling through a nozzle attachment bolt, the aft polar boss and the insulator as the grain prevented measurement through the forward polar boss.
- An SEP-designed and manufactured nozzle featuring a free-standing 4D ITE, and a nested-cone C-C extendible exit cone of involute construction. The extension was deployed by innovative Kevlar®-reinforced rubber flexible tube pneumatic actuators. The actuators were inflated by pyrotechnic squibs fired within them to generate gas. The extendible cone was locked into place with a C-C snap ring.

The vacuum-corrected specific impulse of 303 lbf-sec/lbm, realized during test in the USAF altitude cell at Edwards AFB, was the highest ever up to that time for an SRM. Demonstrated technologies were applied by both companies to succeeding SRM designs.

All-Composite Space Motor Demonstration. The success of the Advanced Space Motor led to a second advanced technologies IR&D demonstration motor, the All-composite Space Motor (figure 4).[4] The following advanced technology components were incorporated into this motor:

- An SEP composite aft polar boss composed of aluminum oxide reinforcements in a carbon matrix. The advantage is a hot-operating nozzle can be directly attached without an intermediate insulator. The chamber was an elongated derivative of that used in the prior program, Kevlar® filament-wound with a carbon-epoxy skirt. Low-density chamber insulation (0.85 g/cc) was used in the forward half, standard density (1.1 g/cc) in the aft. Chamber pressure measurement was via a hole drilled through the composite boss.
- The SEP nozzle, which was threaded directly to the composite polar boss, was ultra-lightweight featuring a free-standing 4D C-C ITE, a membrane exit cone, and a Bell Aerospace-contributed Ta-W gas-deployed skirt. The 2-mm thick membrane exit was composed of carbon cloth patterns formed into a cone and joined together by carbon matrix deposited by chemical vapor infiltration.
- A CSD nozzle-mounted, consumable, toroidal igniter to ignite the head-end web grain of the same 90% solids, 20% aluminum, 12% HMX propellant used in the first technology demonstration motor. Again the propellant was cast into the SEP-provided chamber at CSD.

The motor was test fired in the Edwards AFB test cell while spinning at 75 rpm. All components except the gas-deployed skirt performed successfully (figure 5). The skirt failed due to embrittlement and emissivity degradation at 12 sec into the 42-sec test, identifying the need for a material change for other applications.

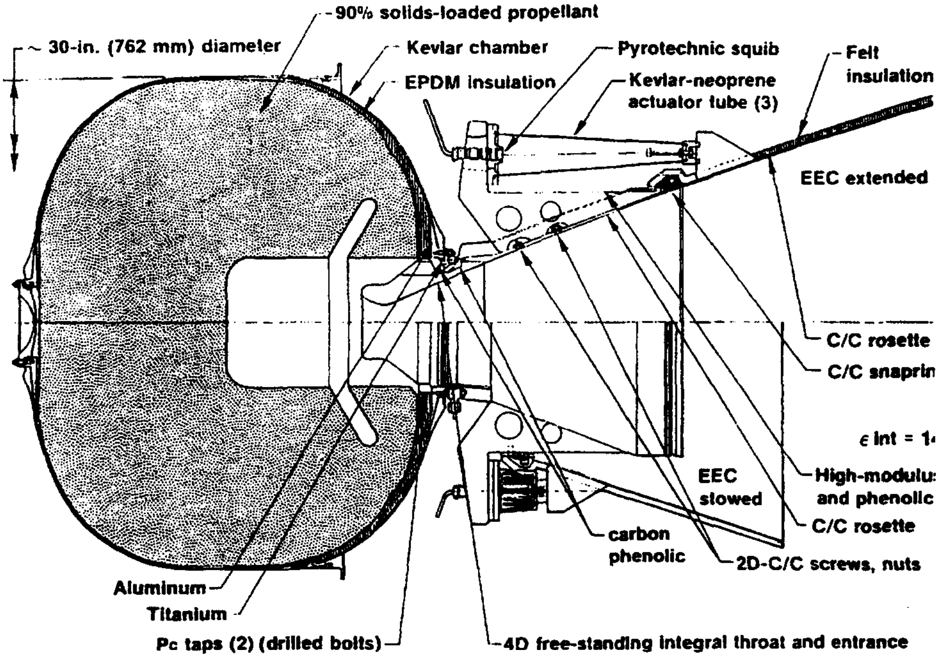


Figure 3. Advanced Space Motor Design

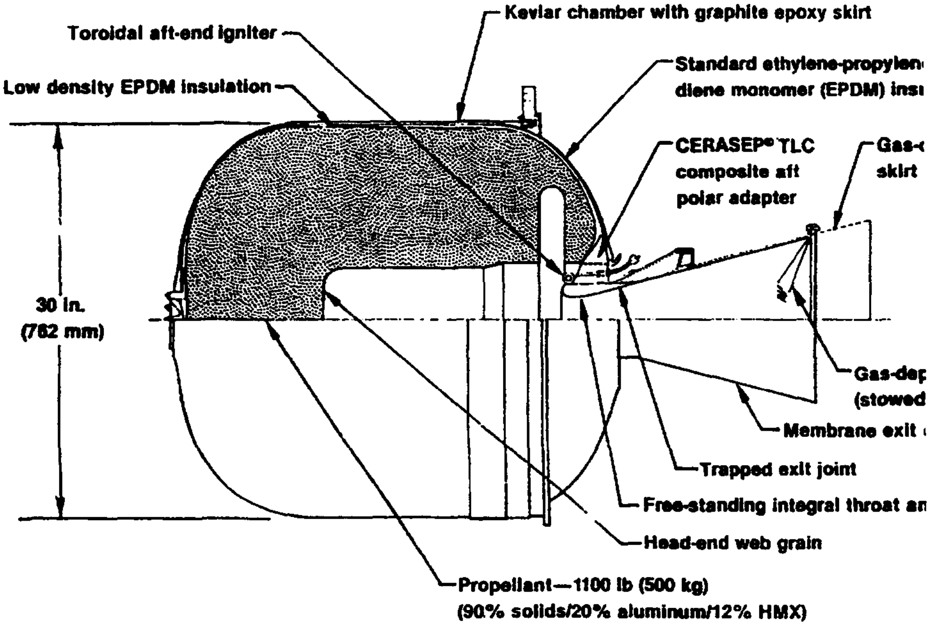


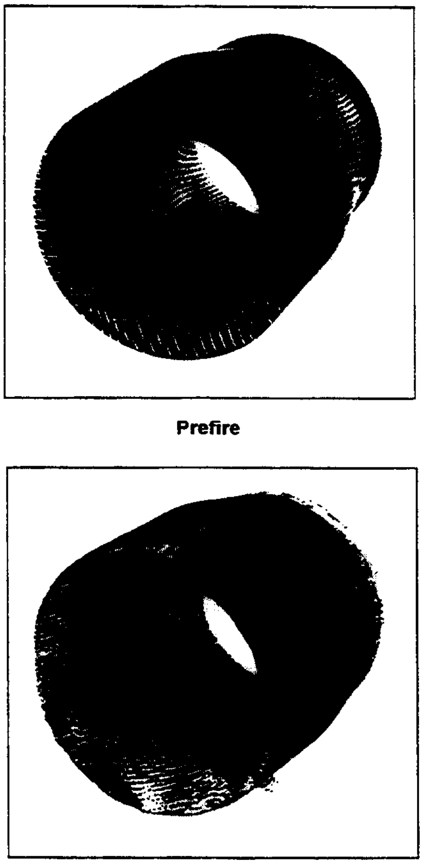
Figure 4. All-Composite Space Motor Design

Figure 5. All-Composite Space Motor, Postfire

Again both companies benefited by being able to apply the successfully-demonstrated technologies to future SRM designs.

Evaluation of 4D and 6D C-C ITE Performance. In 1982 SEP contracted with CSD for the test firing of ITEs of various construction to measure erosion rate as a function of ITE construction and propellant formulation. The normalized results showed an increase in erosion rate of up to 20% when the rod size in 4D ITEs increased from 1 to 3 mm, and over a 40% decrease with propellant containing 12% HMX versus no HMX. Prefire and postfire appearance of one of the ITEs is shown in figure 6. This information was useful to both companies for subsequent designs.

Evaluation of French C-C Exit Cone Technology. Success in the projects described above, jointly funded by the two companies, led to sponsored projects in which both companies were involved. The USAF funded CSD in the 1983–84 period to evaluate materials, designs, and processing used by SEP in C-C exit cone manufacture. CSD purchased a fullscale exit cone (figure 7), a small cylinder, and flat panels of C-C as well as precursor and partially processed materials. Additional processing of materials not fully processed was carried out by US fabricators. The resulting C-C materials were then compared in laboratory tests to determine differences and the relative influence of materials and processes on those differences. Results led to the conclusion US and French C-C technology levels were comparable.



Prefire

Postfire

Figure 6. Test Firing Evaluation of ITEs

Ultra-lightweight Membrane Exit Cone Firing Demonstration. The success of the membrane exit cone in the all-composite space motor demonstration led to sponsorship by the USAF of a large-scale (0.55 m exit diameter) CSD-SEP firing demonstration in 1984. The membrane exit cone (figures 8 and 9) minimizes weight by beginning with a thin shell (membrane), typically 2-mm thick, and adding structures for attachment, TVC loads, etc., only where required. The added structures are structurally tied to the membrane with a combination of graphite cement and carbon matrix deposited by CVI.

The membrane exit cone performed successfully for 48 sec at which time the test motor (surplus) suffered an aft-dome burnthrough unrelated to the nozzle, terminating the test prematurely.

Figure 7. SEP Involute Exit Cone

Figure 8. Membrane Exit Cone, Pre-assembly

Tomahawk. The successful demonstrations of SEP 4D C-C ITEs noted above led to qualification of SEP 4D ITEs for Tomahawk booster SRMs produced by CSD. A large number of these ITEs were used in motors deployed during the 1980's.

Novoltex® Integral Throat and Exit Cone (ITEC) Demonstration. Potential advantages of the SEP Novoltex® Sepcarb® low-cost 3D C-C material, developed in the early 1980's, were recognized and the USAF funded CSD to evaluate the material. The configuration selected for demonstration was the ITEC design (figure 10) in which virtually the entire flow path from leading edge to exit plane is a single component. This configuration demonstrated the capability of the Novoltex® fabrication method to accommodate radical changes in thickness in a single billet.

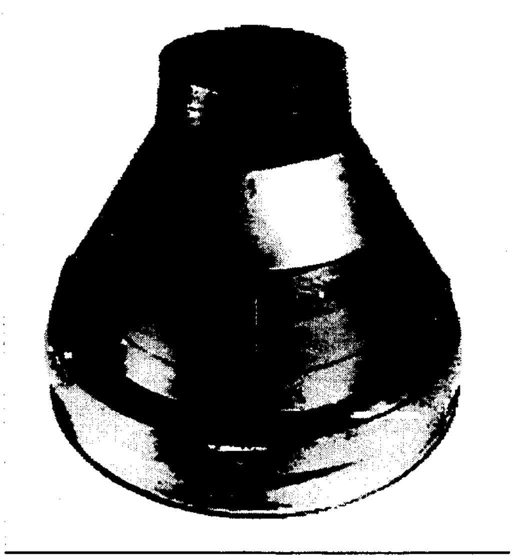


Figure 9. Membrane Exit Cone

In this case the thickness stepped from about 25 mm in the throat-entrance region to only 1.7 mm in the exit cone region. Throat diameter was 171 mm, exit plane diameter 554 mm.

A pair of ITECs of the above geometry produced by SEP were evaluated by CSD. One was test fired successfully in a 63-sec test whereas the other was dissected for property measurements. The demonstrated performance and attractive property values led to additional applications of the material by both companies.

Composite Polar Boss and Hot Gas Valve Demonstration. Two additional applications of Novoltex® Sepcarb® were demonstrated in a USAF-funded CSD program in the late 1980's-early 1990's.[5] One was the use of a low-density version as a composite aft polar boss for a filament-wound chamber. CSD purchased the polar boss from SEP and wound it into an Orbus® 1 carbon-epoxy chamber (figure 11). Like the composite polar boss demonstrated in the all-composite space motor, this allowed direct attachment of a hot-operating nozzle to the chamber.

SEP, during this same period, had applied different versions of Novoltex® Sepcarb® to the design of a composite hot gas valve, and successfully demonstrated it in firing tests. The composite hot gas valve was composed of a 4D pintle tip threaded into a low density insulative version of Novoltex® Sepcarb®, similar to that used in the composite polar boss. CSD elected to use the SEP-developed valve in a nozzle to demonstrate chamber bleed hot gas TVC, and contracted with SEP for the nozzle.

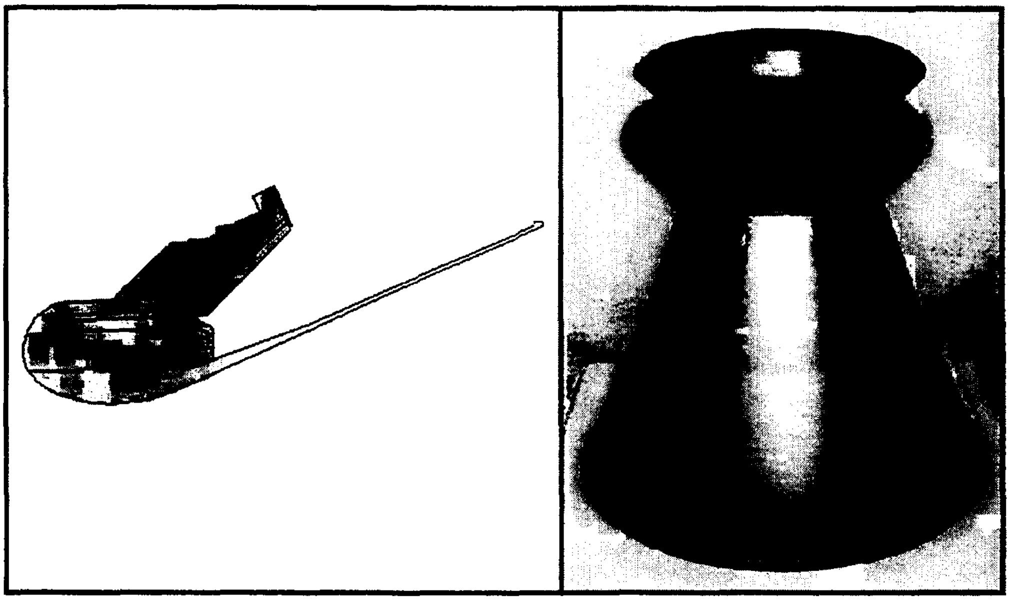


Figure 10. Integral Throat and Exit Cone (ITEC)

The nozzle (figure 12) was composed of a Novoltex® Sepcarb® integral throat support and exit cone (ITSE), a 4D ITE and two SEP hot gas valves, mounted 180-deg apart. The ITSE exploited the capability of Novoltex® Sepcarb® to accommodate radical thickness changes in a single part. The forward part had a wall thickness of over 25-mm to allow flow paths which supplied hot chamber gas to the valves to be drilled into it, parallel to the nozzle axis. The outer surface of the forward part of the ITSE was threaded to match the threads of the composite polar boss discussed above so that the motor could be used for the test of this nozzle. The thick part continued aft to allow mounting provisions for the valves to be incorporated as well as 4D C-C valve seats. The ITSE then tapered down to an exit cone thickness of 5 mm.

Two CSD motors and SEP nozzles were manufactured and successfully test fired. The tests demonstrated the readiness of the composite polar boss combined with the simple two-piece (ITE and ITSE) nozzle for SRM application to greatly simplify designs. The tests further demonstrated the feasibility of chamber bleed hot gas TVC and identified desirable improvements to the design to make this technology ready for application.

Carbon-Carbon Translating Extension for the RL10B-2 Liquid Rocket Engine. Cooperation was not limited to SRMs. Carbon-carbon extendible exit cone technology, originally developed and demonstrated by both companies for SRMs, was applied to a liquid rocket engine, the RL10B-2 liquid oxygen/liquid hydrogen upper stage for the Boeing Delta III and IV launch vehicles.[6–10] As noted above, SEP and CSD jointly demonstrated an extendible exit in 1979. Numerous independent efforts related to this technology were also accomplished allowing the two companies to apply their joint experience to this application.

Figure 11. Composite Polar Boss

The RL10B-2 translating nozzle extension (figure 13) is significantly larger than any previous, nearly 2.5 m (100 in.) in length with an exit diameter of 2.1 m (84 in.). Composed of a fixed section 22.1 in. (570 mm) long and a trans-

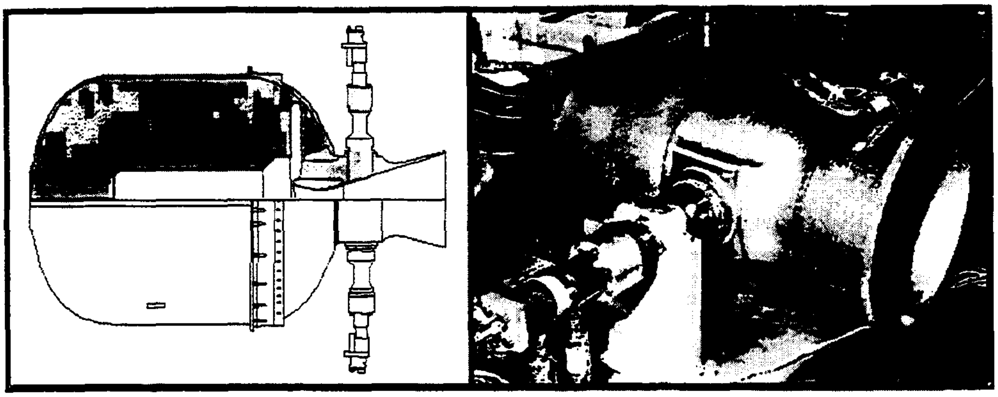
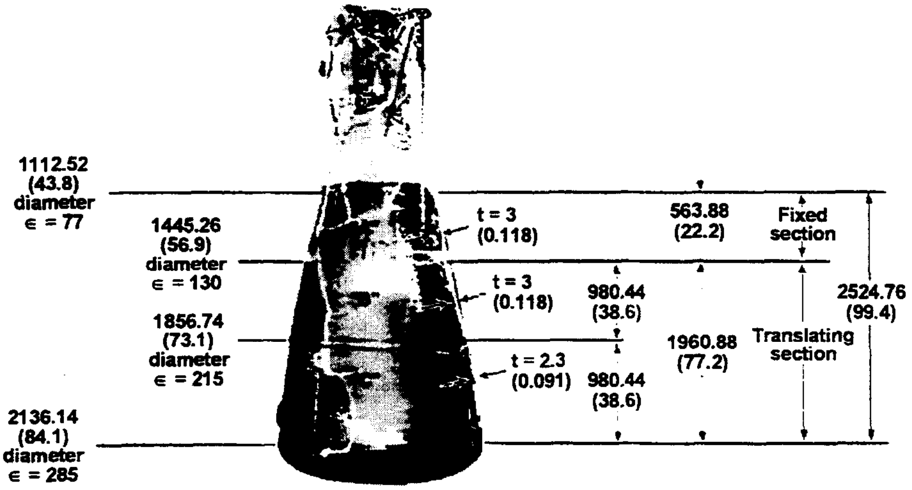


Figure 12. Motor with Composite Polar Boss and Hot Gas Valve Nozzle



Notes: Dimensions are in millimeters
Dimensions in parentheses are in inches

Figure 13. RL10B-2 Engine with Nozzle Extension

lating section 77.2 in. (2082 mm) long, the extension increases the expansion ratio from 77:1 at the engine regenerative primary nozzle exit plane to 285:1, adding about 30 seconds of specific impulse. In the stowed position during the boost phase of the launch, the translating section almost completely envelops the base engine and fixed extension thereby reducing interstage height. Novoltex® Sepcarb®, with its previous successful use history noted, in part, above, was selected for the nozzle. The excellent properties of this material allowed the basic wall thickness to be reduced to only 2.3 mm (0.090 in.) in the portion near the exit plane, and only 3 mm (0.117 in.) in the forward portions.

This nozzle extension underwent 17 successful altitude cell firing tests (figure 14) as part of Delta III flight qualification prior to successful flight, and will soon undergo 4 additional altitude cell firings to validate processing simplifications prior to Delta IV flights scheduled next year. Over 20 nozzle extensions have been produced by SEP to date and delivered to CSD.

Supersonic Splitline Flexseal Nozzle In the mid 1990's, CSD, with SEP as the pre-selected nozzle subcontractor, was awarded an Integrated High Payoff Rocket Propulsion Technology (IHPRPT) contract by the USAF to demonstrate the performance, cost, and reliability advantages of the supersonic splitline flexseal nozzle (figure 15). The nozzle was successfully test fired in May 1997 incorpo-

Figure 14. RL10B-2 Nozzle Extension Simulated Altitude Test Firing

rated in a CSD Orbus®1 motor with a CSD electro-mechanical thrust vector actuation system.[11] The motor, nozzle, and actuation system all performed successfully. The potential for significant performance and cost improvements was demonstrated.

A scale-up of the supersonic splitline nozzle is now funded by the USAF as part of a follow-on IHRRPT program. The nozzle will be designed by a Joint Integrated Product Team including both Snecma and CSD, and key components will be supplied by Snecma. Test firing demonstration is scheduled during 2003.

LESSONS LEARNED, RULES FOR SUCCESS

Many factors have contributed to the success of the SEP-CSD relationship, discussed above, which has now evolved into a similarly successful relationship between Pratt & Whitney and Snecma as CSD became part of Pratt & Whitney and SEP part of Snecma. Some of the key factors are as follows.

Win-Win Projects. Projects must be selected and planned carefully so that each company benefits, and the mutual benefits are clearly understood. In our relationship, sharing of expenses to pursue technology enabled the accomplishment of many projects that otherwise would not have been undertaken, or that would have been undertaken at a slower pace. Another type of win-win situation was exhibited by the RL10B-2 nozzle extension program. SEP

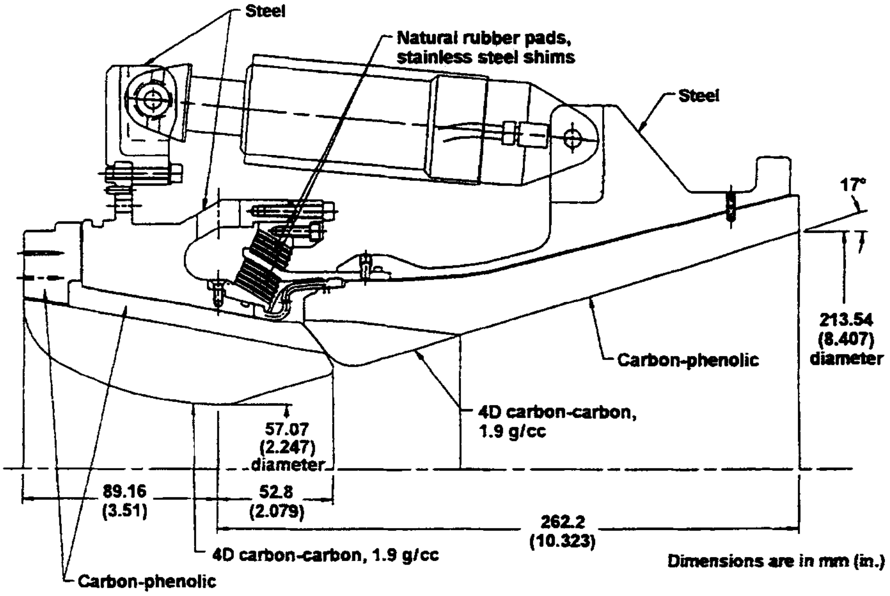


Figure 15. Supersonic Splitline Flexseal Nozzle

had the only existing and available facilities large enough to manufacture the size needed by CSD, and the proven material technology to achieve the needed properties. With facilities in existence, and by jointly developing the design in parallel with manufacture of billets, the first nozzle extension was delivered only one year after initiation of the effort. Without the teamwork made possible by the relationship developed by the previous joint efforts, the first delivery likely would have been more than a year later.

Mutual Respect and Courtesy. A key to success was the development of mutual respect for the experience and talents of the partner. Both partners quickly learned the other had different ways of doing things, and the different way was often better. "Different is not wrong" is a necessary attitude for success. There is no room for arrogance or chauvinism if such a partnership is to be successful.

Appreciation of cultural differences, and courtesy with respect to these, is required. Consistent use of dual units (metric and US) in drawings and reports requires little extra time but is very effective in facilitating communication and helping to prevent errors. This policy was carried into the documents of sponsored as well as joint independent efforts, even when not required by the sponsor.

Patience and Flexibility. Great patience and flexibility have proven to be necessary qualities for success in international cooperation. Time must be allotted in the planning of projects for the extra layers of approvals required such as export and import and other Government approvals on both sides. Approvals, when eventually received, can often be conditional, so it is necessary to be ready for changes in the structuring of projects. We learned to apply our experience to facilitate projects. Government approvals were applied for very early. In several recent sponsored joint projects, Government approvals were applied for early enough that CSD was able to initiate SEP work the same day the contract from the sponsor was received by CSD. In at least one case, we were able to receive all approvals just before the CSD proposal was submitted to the potential sponsor.

CONCLUSION

A successful international cooperative relationship between SEP and CSD has continued for over twenty-five years, and continues today as the companies have become Snecma and Pratt & Whitney. Over a dozen joint projects have been successfully accomplished. The companies have demonstrated that with mutual respect, courtesy, patience, and flexibility, international cooperation can be mutually rewarding.

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