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Liquid Fluorine Feed System Component Design Criteria

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FORMULATION of the basic design criteria for flightweight fluorine feed systems began in 1965,[1] and the valve-related technology included evaluation of existing valves, and testing of two reworked off-the-shelf valves. In a continuation program,[2] conceptual design studies were directed toward a shutoff valve optimized for service with oxidizers containing liquid fluorine (LF_2). The latest effort included the design and fabrication of two test valves, with LF_2 tests of 250 cycles for one and 840 cycles for the other, which demonstrated the accuracy and utility of the criteria. Fabrication and acceptance testing was subcontracted to the Systems Division of Parker Hannifin, Los Angeles.

High reactivity of liquid fluorine requires specific consideration for specific design areas. A material in a fluorine environment must not exceed its ignition temperature, Table 1. Because the mass of material (available heat sink) in flightweight components is small, materials with a relatively high heat-transfer coefficient are needed for fluorine service. For critical component areas near high heat sources, the common stainless steels and Monels are less desirable than nickel, Inconel, copper, and aluminum.[3]

Table 1 Ignition temperatures of selected metals in fluorine

Metal	Melting point, °F	Average ignition temperature, °F	% maximum variation from average
Aluminum	1200	1382[a]	—
Copper	1980	1277	8.0
Iron	2780	1242	0.8
Molybdenum	4740	378	8.3
Monel	2400	755	12
Nickel	2620	2091	6
302 Stainless steel	2570	1259	13
Tungsten	6170	496	18

[a] An average of four tests gave an ignition temperature greater than melting point of aluminum.

Use of metal gaskets and seals rather than plastic materials such as Teflon, Kel F, etc., is recommended. Because no compatible lubricant is available for assembling the metal parts, no seal configuration should be used which requires a turning motion that might cause galling. A plating of soft gold, copper, or silver on one of the surfaces should be specified to accommodate some sliding motion. Nonsliding seals such as bellows, diaphragms, etc., are recommended for all components where relative motion occurs between two parts. All parts are designed so that all surfaces can be cleaned and inspected easily. A one-piece design without cavities is preferred. A cavity should be sealed by welding or brazing, and a 100% x-ray inspection specified to ensure the quality of welds. Dye penetrants should not be used, because they cannot be completely removed by normal cleaning procedures, and the residue may cause a reaction with fluorine.

Corrosive effects of LF_2 on the common structural materials do not normally present a problem. The anhydrous form of the common impurity HF does not produce high rates of corrosion, but aqueous HF is very corrosive; great care must be taken to prevent moisture from entering the fluorine system. It is recommended that no subcomponent be prepassivated as there is no way to prevent the fluoride film from absorbing atmosphere moisture before installation into the system.

Valve Design and Test Results

Valve design objectives and specifications are shown in Table 2. For preliminary helium leak testing, a leak rate of 10^{-8} lb/sec of *G*He at −320°F was selected (on the basis of experience) as equivalent to the 10^{-7} lb/sec fluorine leakage requirement. The basic 2-in. valve configuration (Fig. 1) consists of a 90° offset poppet design weighing ~10 lb. The valve body is an Inconel 718 weld assembly made of two lathe-turned subcomponents. The surfaces that mate with the static seals must be free of porosity and have a surface finish of 16 μin. AA maximum. The static seals are of two functional types: those directly exposed to F_2 during normal

Table 2 Valve design objectives and specifications

	NAS3-11195	NAS3-12029
Fluid	LF_2, *LOX*, *FLOX* (MIL-P-27401)	Same
Temperature (fluid)	−320°F	Same
Fluid pressure, oxidizer	100 psig max. operating	Same
	250 psig proof	Same
	375 psig burst	Same
Actuation, helium	500 psig max. operating	500 psig operating
	600 psig proof	750 psig proof
	750 psig burst	1125 psig burst
Flow rate	90 gpm	60 gpm
Pressure differential at rated flow	10 psig max.	5 psig max.
	5 psig target	
Line size	2-in. i.d.	Same
Leakage rate		
A) Propellant to actuator	0 SCIM He	Same
B) Main seat internal leakage	10^{-6} PPS F_2	10^{-7} PPS F_2
Actuation time (maximum)	75 msec	Same
Fail safe	Closed	Same

Received July 14, 1970; presented as Paper 70-705 at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, Calif., June 15–19, 1970; revision received January 4, 1971. Work supported by NASA under Contracts NASw-1351, NAS3-11195, and NAS3-12029.

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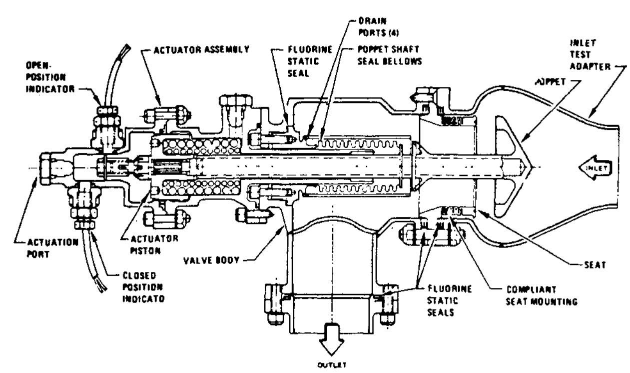

Fig. 1 Space storable oxidizer valve design.

use of the valve and those exposed to F_2 if a failure occurs that permits F_2 leakage into areas not normally exposed. A gold-plated Inconel "W" ring seal was specified for the former.

The Inconel 718 poppet consists of a rigid conical structure machined integral with a tubular shaft. A relatively wide, flat-sealing land is machined on the base of the cone with the conical apex pointed upstream into the propellant flow. The valve seal consists of a rigid (A286) ring with a flat-sealing land machined on the face to mate with the poppet. The machined bellows mounting provides for poppet-to-seat alignment. The basic −1 configuration has the Inconel 718 poppet seated on the A286 seal; the −501 configuration version has the seating surface of the seat plated with 23+ carat gold plate. A bumper (Fig. 2) accommodates misalignment between the poppet and the compliant seal. This bumper absorbs initial contact loading stresses if the seat misalignment should exceed 0.8° relative to the poppet face. A hydroformed Inconel bellows seals the poppet shaft, thus isolating the actuator from the fluorine cavity of the valve. The bellows acts as a centering member for the main poppet shaft, permitting a relatively loose fit for the inboard guide bushing.

The tests in LF_2 were conducted at the MDAC A-23 Fluorine Test Facility. Both valves performed within the design specification throughout the 100-psig, 250-cycle life tests; no disassembly or adjustment was required. Although the valves are designed for operation at 100 psig, a complete leakage profile was made from 25 psig to the proof pressure condition of 250 psig as shown in Fig. 3. Figure 4 indicates that change in leakage measured after cycling the −501 valve corresponds to a change in surface roughness for the gold plating from 1.3-μin. finish (No. 1) to 0.6-μin. (No. 2). The bandwidth shown for each test point indicates

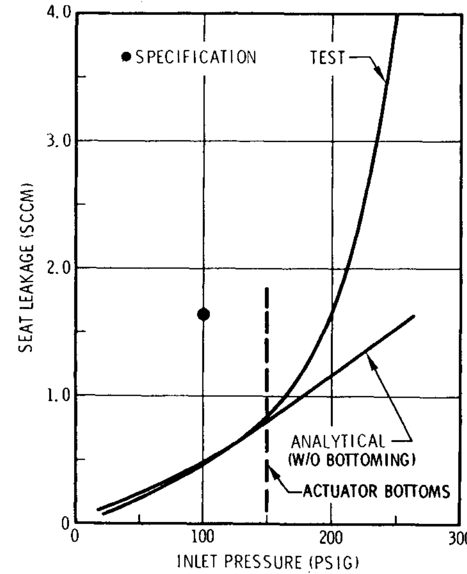

Fig. 3 Valve internal leakage at −320°F −501 after 373 cycles (corrected to 100 psig performance).

the probable range of uncertainty. No change in leakage was detected as a result of the passivation process, but a significant decrease occurred with operation in LF_2. The 23+-carat gold plating on the −501 configuration fulfilled the high cycle-life requirement. A 24-carat gold plating would likely be better for valves with lower cycle-life requirements because this material is softer and requires less cycling to obtain good conformance to the seal interface. After completing 590 of the scheduled 750 proof-pressure cycles at 250 psig, the −1 valve failed to open at cycle 591 because of leakage of the actuator piston seal. Fluorine had entered the actuator through a small fatigue crack that developed in the shaft seal bellows due to the "ringing" effect resulting from the poppet assembly bottoming on the actuator end cap. This effect resulted from proof-pressure loading conditions and would not occur under normal pressure balancing conditions.

Conclusions

Design criteria for fluorine feed system components for use in high-energy upper-stage propulsion systems have been developed and validated by ground testing. The low leakage requirement of 10^{-7} lb/sec of fluorine at cryogenic temperatures was met successfully in a 2-in. shut-off valve with a flat-on-flat poppet-valve configuration.

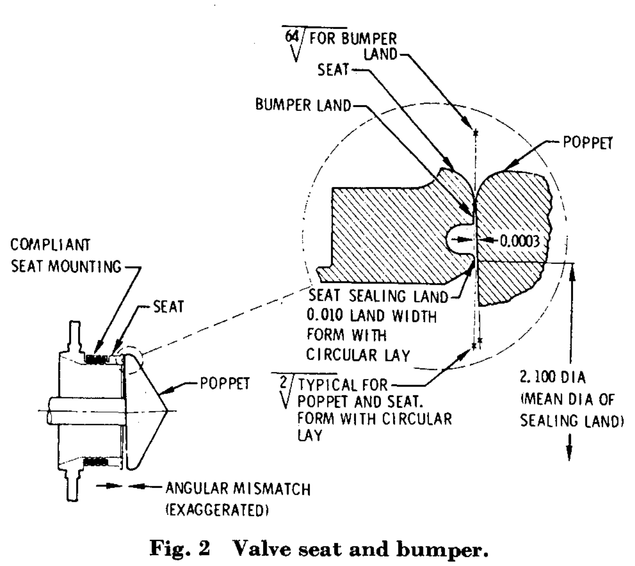

Fig. 2 Valve seat and bumper.

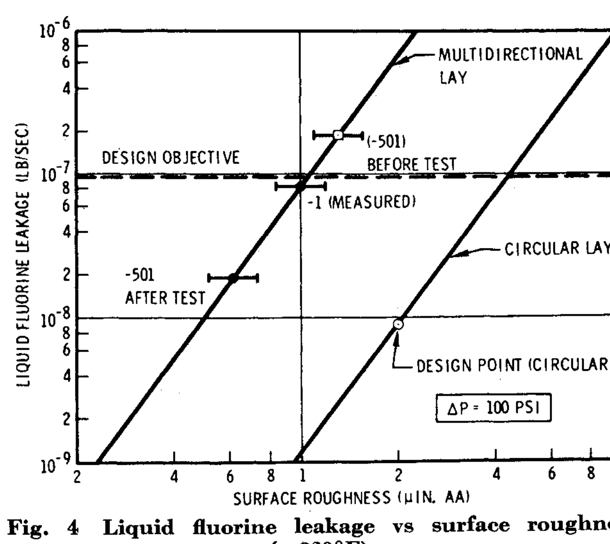

Fig. 4 Liquid fluorine leakage vs surface roughness (−320°F).

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Injector Design Criteria Using Noncircular Orifice Geometry

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The most commonly used rocket engine injector designs in existence today employ circular orifices. However, with the advent of new fabrication techniques, noncircular orifices can now be produced with relative ease, and it is appropriate to evaluate their possible advantages. This Note presents experimental data on single-element cold-flow spray patterns evaluation and predicted performance differences among several noncircular and circular orifice configurations.

In the experimental technique employed, molten wax is used as one propellant simulant and hot water as the other. The spray of wax and water emanating from an injector is allowed to flow through the air for a time sufficient to allow the wax droplets to freeze. The frozen wax droplets are then caught on a platform, washed down into a particle catch basin, dried, weighed, and segregated by sieving.

Mixing efficiency of the injector elements was measured by collecting the spray from the element while flowing water and trichloroethylene. These fluids are immiscible. The spray is collected through an 841-tube matrix in separate glass tubes, and the mixture ratio in each tube is recorded. The injectors are mounted 3 in. above the collection matrix.

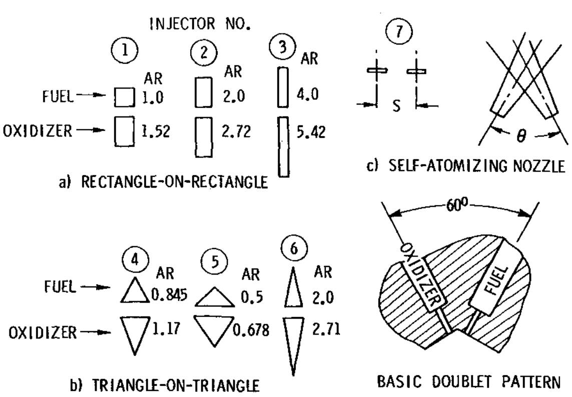

Fig. 1 Summary of injector patterns.

Injector elements tested (Fig. 1) were unlike-impinging doublets and self-atomizing nozzles. In addition, an unlike doublet with circular orifices was tested to establish a reference point for comparison. Rectangular and triangular patterns were designed at several orifice aspect ratios (AR = height/width ratio of an orifice). For the triangular and rectangular elements, the widths of the two orifices in a given doublet were equal, and θ, the included angle of impingement, was set at 60°. The self-atomizing orifices were tested over ranges of spacing and impingement angle as shown in Fig. 1.

Results and Discussion

Mixing results

Results of cold-flow mixing studies conducted with the unlike doublets are presented in Fig. 2. Mixing uniformity E_m is correlated with a momentum ratio term N. Mixture ratio distribution uniformity E_m originally developed by Rupe at JPL[1] is defined by Eq. (1);

$$E_m = 100\left[1 - \sum_i^N MF_i \frac{R - r_i}{R} - \sum_i^{\bar{N}} MF_i \frac{R - r_i}{R - 1}\right] \quad (1)$$

where MF_i = mass fraction in ith tube; R = over-all mass ratio, trichloroethylene/trichloroethylene and water; r_i = mass ratio in ith tube, trichloroethylene/trichloroethylene and water; N = number of tubes in which $r < R$; and $\bar{N}$ = number of tubes in which $r > R$. The momentum ratio term N is given by the expression[2]

$$N = [1 + (M_f/M_0)(D_0/D_f)]^{-1} \quad (2)$$

where M_f/M_0 = fuel-to-oxidizer momentum ratio, and D_0/D_f = oxidizer-to-fuel orifice hydraulic diameter ratio (4 × area/perimeter = hydraulic diameter).

Results presented in Fig. 2 for unlike doublets of the impinging-type show that mixture ratio uniformity optimizes at N = 0.5 for noncircular orifices. For the spray fan injector (orifice spacing = 1 in.), mixing optimizes at an impingement angle of 60° included. As noted in Fig. 2, the level of mixing varies with orifice aspect ratio as well as with N.

Drop size results

Figure 3 presents atomization data for the specific elements which produced the highest mixing levels (i.e., numbers 2 and 4). Mass median droplet diameter decreases as the relative velocity between injectant and environmental gas increases. For the impinging-type elements, the rectangles produce droplets which are slightly smaller than the triangles.

Comparison of spray characteristics for optimized elements

The determination of the optimum injector design requires that all elements be designed according to Eq. (2) with N

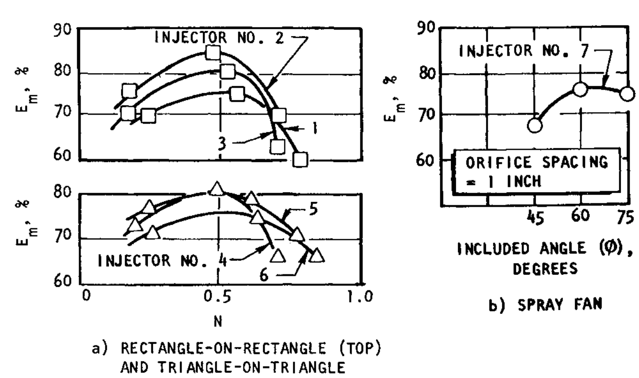

Fig. 2 Single-element mixing results.

Received July 24, 1970; revision received September 8, 1970. Sponsored by NASA Manned Spacecraft Center, Houston, under initial Contract NAS9-9528; the NASA Technical Manager is M. Lausten.

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