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SPACE VEHICLE
DESIGN CRITERIA
(CHEMICAL PROPULSION)

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LIQUID ROCKET VALVE ASSEMBLIES

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FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, part of the series on Chemical Propulsion, is one such monograph. A list of all monographs issued prior to this one can be found on the final pages of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that these documents, revised as experience may indicate to be desirable, eventually will provide uniform design practices for NASA space vehicles.

This monograph, "Liquid Rocket Valve Assemblies", was prepared under the direction of Howard W. Douglass, Chief, Design Criteria Office, Lewis Research Center; project management was by M. Murray Bailey. The monograph was written by T. R. Spring, Rocketdyne Division, Rockwell International Corporation and was edited by Russell B. Keller, Jr. of Lewis. To assure technical accuracy of this document, scientists and engineers throughout the technical community participated in interviews, consultations, and critical review of the text. In particular, O. D. Goodman of Aerojet Liquid Rocket Company; D. K. Huzel of the Space Division of Rockwell International Corporation; T. M. Weathers of TRW Systems, TRW Inc.; and C. H. Kerrigan of the Lewis Research Center individually and collectively reviewed the monograph in detail.

Comments concerning the technical content of this monograph will be welcomed by the National Aeronautics and Space Administration, Lewis Research Center (Design Criteria Office), Cleveland, Ohio 44135.

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GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in design, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into two major sections that are preceded by a brief introduction and complemented by a set of references.

The State of the Art, section 2, reviews and discusses the total design problem, and identifies which design elements are involved in successful design. It describes succinctly the current technology pertaining to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Design Criteria* and Recommended Practices.

The *Design Criteria*, shown in italics in section 3, state clearly and briefly what rule, guide, limitation, or standard must be imposed on each essential design element to assure successful design. The *Design Criteria* can serve effectively as a checklist of rules for the project manager to use in guiding a design or in assessing its adequacy.

The Recommended Practices, also in section 3, state how to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The Recommended Practices, in conjunction with the *Design Criteria,* provide positive guidance to the practicing designer on how to achieve successful design.

Both sections have been organized into decimally numbered subsections so that the subjects within similarly numbered subsections correspond from section to section. The format for the Contents displays this continuity of subject in such a way that a particular aspect of design can be followed through both sections as a discrete subject.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the designer.

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LIQUID ROCKET VALVE ASSEMBLIES

1. INTRODUCTION

The valves used in the fluid-control systems for liquid rocket engines must meet special requirements in order to function reliably in the severe operating environment. The designer of a new valve thus is confronted by a number of major problems that require effective solutions. In a typical new design, for example, he must

- Meet the sealing requirements (satisfy the permissible leakage rate)
- Achieve the allowable pressure drop
- Select materials to withstand fluid corrosiveness, environmental exposure, and engine operating conditions
- Design and integrate housing and valving unit assemblies that exhibit minimum distortion from internal pressures, imposed loads at interface connect points, actuating force, and thermally induced loads
- Predict transient pressures and flow anomalies resulting from interaction of components of the flow system
- Establish accurately the dynamic loads on valving elements, friction loads on bearings and journals, and friction in the linkage and actuator under steady-state and transient thermal conditions
- Select an actuator that will meet the response time and actuation requirements over the most extreme conditions of the mission duty cycle (and also provide for some degree of uprating)
- Incorporate into the design adequate life for projected engine and stage or spacecraft checkout operations in both the dry and wet modes.

This monograph sets forth the current technology for solving these and other problems in the design of valves that are to be utilized for control of rocket engine systems in boosters, upper stages, and spacecraft; in addition, it treats valves such as prevalves and pressurization system on-off valves associated with vehicle propellant tankage. The design of other specialized valves including pressure regulators, check valves, and one-shot normally closed valves and burst disks is treated in reference 1. The monograph is limited to valve selection factors for trade studies, configuration analysis, actuator selection, and integration of components. The detailed design of individual valve components and of valve actuators and operators is presented in other design criteria monographs suitably referenced throughout this document.

The material in this monograph is organized along lines of the valve design sequence. A new valve design for a rocket engine propellant, pressurization, or hydraulic/pneumatic control system starts with a configuration analysis utilizing accurate design requirements that result from the analysis of the engine control system. A preliminary layout with supporting calculations results from the configuration analysis. The next step is a detailed functional analysis by which the various components of the valve are sized. The design criteria monograph "Liquid Rocket Valve Components" (ref. 2) treats the individual component functional analysis and the final design and analysis phase that extends the functional analysis into actual detailing of drawings and preparation of specifications necessary to fabricate the individual components of the valve. This "Valve Assemblies" monograph provides the insight and capability for integration of these valve components and for actuator sizing. Final design reviews complete the design analysis phase, and drawings are released for valve fabrication and assembly.

After a valve design is released, the designer's tasks include fabrication follow-up, prototype assembly, valve development, and qualification of the final design. Valves used in the qualification test phase must be fabricated and assembled by production techniques so that no pitfalls are created by qualifying hardware that is not representative of the production-version valve. Successful completion of the testing, problem solving, and corrective action phases culminates in a production-version valve assembly capable of performing reliably in the operational rocket engine system.

2. STATE OF THE ART

The valving for liquid rocket engine propellant and pressurant systems encompasses a variety of valving unit and actuator combinations; valve functions include shutoff, routing of flow, and throttling[1]. Table I lists typical propellant and pressurant valves used on representative operational booster, upper-stage, and spacecraft propulsion systems. As shown in the table, the valving units in present operational propulsion systems include the following types:

- Poppet (including cavitating venturi)
- Butterfly
- Ball
- Blade (rotary or linear)
- Sleeve (linear travel or rotary travel)
- Spool, cylindrical slide or piston (sequence valves)
- Plug (explosive-actuated normally open valve)

The service fluids for these valving units include cryogenic, earth-storable, and space-storable propellants; hydraulic fluids; pressurizing gases; and hot-gas combustion products.

Review of Table I shows that the valve selected for the main valves in booster engine thrust chambers has been predominantly the butterfly type, with the exception of the balanced poppet valves utilized on the F-1 engine. For thrust-chamber main valves on upper-stage engines, butterfly, ball, and poppet valves have been selected. For reaction control systems (RCS), poppet valves have been the exclusive selection. Designers of landing-craft propulsion systems have utilized both poppet and ball valves in redundant assemblies. Hydraulic and pneumatic control systems for these engines incorporate almost exclusively poppet valves.

The most widely used basic valving unit types – poppet, butterfly, and ball – evolved from industrial control applications. Of the three, the poppet has proved to be the most reliable and versatile unit for rocket engine fluid control, having been used in all propulsion system applications with the exception of the large propellant prevalves.

For use in rocket systems, the butterfly valve design has been improved to achieve tight shutoff and reduced seal wear by off-center eccentric disk motion. The butterfly valve is used primarily in one-start booster propulsion systems, although butterfly valves in the

[1]Terms, symbols, materials, and abbreviations used herein are identified in the Glossary.

Table I. - Design Features of Representative Operational Valve Assemblies

Vehicle and engine	Valve use	Valving element	Line size, in.	Line size, mm	Operating pressure, psi	Operating pressure, kN/m^2	Flowrate, lb/sec	Flowrate, kg/sec	Service fluid	Actuator type	Actuator fluid	Response time, msec
					Booster Systems							
Atlas												
MA-5 (Two-chamber booster and separate sustainer)	Booster MOV	Butterfly	4.00	101.6	782	5392	424.5	192.55	LOX	Pneumatic piston	He	400
	Booster MFV	Butterfly	4.0	101.6	792	5461	178.3	80.88	RP-1	Pneumatic piston	He	100
	Booster GG bipropellant	Blade	0.75	19.1	570	3930	7.27	3.30	LOX	Pneumatic piston	He	350
		Blade	1.00	25.40	575	3965	19.96	9.05	RP-1	Pneumatic piston	He	350
	Sustainer HS	Butterfly	3.00	76.20	1000	6895	183.0	83.01	LOX	Hydraulic piston	Oil	500
	Sustainer PU	Butterfly	3.0	76.20	1000	6895	74.0	33.57	RP-1	Hydraulic piston	Oil	500
	Sustainer GG bipropellant	Blade	0.75	19.1	835	5757	2.12	0.96	LOX	Hydraulic piston	Oil	235
		Blade	1.00	25.40	917	6323	7.58	3.44	RP-1	Hydraulic piston	Oil	235
Thor												
MB-3 (Single engine)	Main oxidizer	Butterfly	4.00	101.6	850	5861	454.0	205.93	LOX	Pneumatic piston	GN_2	60
	Main fuel	Butterfly	4.00	101.6	850	5861	200.0	90.72	RP-1	Pneumatic piston	GN_2	110
	GG bipropellant	Blade	0.75	19.1	652	4496	3.73	1.69	LOX	Pneumatic piston	GN_2	100
		Blade	1.00	25.40	647	4461	11.48	5.21	RP-1	Pneumatic piston	GN_2	100
Titan III												
LR-87-AJ-5 (Cluster of two engines, first stage)	Main oxidizer	Butterfly	5.00	127.0	1042	7185	547.2	248.21	N_2O_4	Mechanically linked to MFV	NA	700
	Main fuel	Butterfly	4.00	101.6	1343	9260	284.5	129.05	A-50	Hydraulic piston	A-50	700
	GG bipropellant	Poppet	0.38	9.65	783	5399	1.02	0.46	N_2O_4	(a)	N_2O_4	–
		Poppet	1.00	25.40	830	5723	12.01	5.45	A-50	(a)	A-50	–
	Oxidizer prevalve	Butterfly	7.00	177.8	150	1034	547.2	248.21	N_2O_4	Explosive	NA	10
	Fuel prevalve	Butterfly	6.00	152.4	150	1034	284.5	129.05	A-50	Explosive	NA	10
LR-91-AJ-5 (Single engine, second stage)	Main oxidizer	Butterfly	4.00	101.6	1098	7571	207.3	94.03	N_2O_4	Mech. linked to MFV	NA	450
	Main fuel	Butterfly	3.00	76.20	1180	8136	115.1	52.21	A-50	Hydraulic piston	A-50	450
	GG bipropellant	Poppet	0.38	9.65	765	5275	4.32	1.96	N_2O_4	(a)	N_2O_4	–
		Poppet	0.75	19.1	670	4620	4.91	2.22	A-50	(a)	A-50	–
	Oxidizer prevalve	Butterfly	6.00	152.4	150	1034	207.3	94.03	N_2O_4	Explosive	NA	10
	Fuel prevalve	Butterfly	4.00	101.6	150	1034	115.1	52.21	A-50	Explosive	NA	10
Saturn S-1B												
H-1 (Cluster of eight H-1 engines)	Main oxidizer	Butterfly	4.00	101.6	975	6723	545.0	247.21	LOX	Hydraulic piston	RP-1	333
	Main fuel	Butterfly	4.00	101.6	975	6723	243.0	110.25	RP-1	Hydraulic piston	RP-1	650
	GG bipropellant	Poppet	0.609	15.47	940	6481	4.61	2.09	LOX	Hydraulic piston	RP-1	120
		Poppet	1.078	27.38	1070	7378	13.52	6.13	RP-1	Hydraulic piston	RP-1	120
Saturn S-1C												
F-1 (Five F-1 engines)	Checkout valve	Ball	2.5	63.5	1600	11032	23.0	10.43	RP-1	Electric motor	NA	3000
	Three-way override	Poppet	0.080	2.03	1500	10343	0.2	0.09	RP-1	Plunger solenoid	NA	50
	4-way control	Spool	1.25	31.75	2060	14204	9.6	4.35	RP-1	Pilot poppet valves with plunger solenoid	RP-1	50
	Main oxidizer	Poppet	8.00	203.2	1600	11032	2000.0	907.2	LOX	Hydraulic piston	RP-1	600
	Main fuel	Poppet	6.00	152.4	1800	12411	830.0	376.49	RP-1	Hydraulic piston	RP-1	600
	GG bipropellant	Ball	1.5	38.1	1600	11032	50.3	22.82	LOX	Hydraulic piston	RP-1	170
		Ball	1.875	47.63	1800	12411	121.5	55.11	RP-1	Hydraulic piston	RP-1	170
	Oxidizer prevalve	Ball (visor)	17.00	431.80	115	793	3970.0	1800.79	LOX	Pneumatic piston	GN_2	500

	Fuel prevalve	Ball (visor)	12.00	304.80	150	1034	890.0	403.70	RP-1	Pneumatic piston	GN_2	500
	Interconnect valve	Ball	4.00	101.6	115	793	–	–	LOX	Pneumatic piston	GN_2	–
	Oxidizer fill and drain	Ball	6.00	152.4	115	793	790.0	358.34	LOX	Pneumatic piston	GN_2	–
	Fuel fill and drain	Ball	6.00	152.4	150	1034	225.0	102.06	RP-1	Pneumatic piston	GN_2	–
Upperstage Systems												
Saturn S-II J-2 (Cluster of five engines)	Main oxidizer	Butterfly	4.00	101.6	911	6281	386.0	175.09	LOX	Pneumatic piston	He	180
	Main fuel	Butterfly	4.00	101.6	1130	7791	78.0	35.38	LH_2	Pneumatic piston	He	140
	GG bipropellant	Poppet	0.531	13.49	1010	6964	3.29	1.49	LOX	Pneumatic bellows	He	190
		Poppet	0.906	23.01	1130	7791	3.5	1.59	LH_2	Pneumatic bellows	He	190
	Oxidizer turbine bypass	Butterfly	5.00	127.0	122	841	5.08	2.30	Hot Gas	Pneumatic bellows	He	5000
	Propellant utilization	Sleeve	2.00	50.80	1310	9032	1 to 120	(b)	LOX	Electric motor	NA	Throttling
	Oxidizer recirculation	Butterfly	2.00	50.80	132	910	–	–	LOX	Pneumatic piston	He	5000
	Fuel recirculation	Butterfly	2.00	50.80	132	910	–	–	LH_2	Pneumatic piston	He	5000
	Oxidizer fill and drain	Butterfly	8.00	203.2	132	910	790.	358.34	LOX	Pneumatic piston	He	12000
	Fuel fill and drain	Butterfly	8.00	203.2	132	910	100.	45.36	LH_2	Pneumatic piston	He	22000
	Oxidizer shutoff prevalve	Butterfly	8.00	203.2	132	910	386.	175.09	LOX	Pneumatic bellows	He	1000
	Fuel shutoff prevalve	Butterfly	8.00	203.2	132	910	78.	35.4	LH_2	Pneumatic bellows	He	1000
Saturn S-IVB J-2 (Single engine)	Oxidizer recirculation	Poppet	2.00	50.80	60	414	–	–	LOX	Pneumatic bellows	He	140
	Fuel recirculation	Poppet	2.00	50.80	60	414	–	–	LH_2	Pneumatic bellows	He	140
	Oxidizer fill and drain	Butterfly	4.00	101.6	60	414	160.	72.6	LOX	Pneumatic piston	He	265
	Fuel fill and drain	Butterfly	4.00	101.6	60	414	30.	14.	LH_2	Pneumatic piston	He	265
	4-way pneumatic control	Poppet	0.25	6.35	400	2758	0.031	0.014	He	Plunger solenoid	NA	22
	3-way pneumatic control	Poppet	0.25	6.35	400	2758	0.005	0.002	He	Plunger solenoid	NA	15
	Fast shutdown	Poppet	0.25	6.35	400	2758	0.03	0.014	He	(c)	He	15
	Purge control	Poppet	0.25	6.35	400	2758	0.03	0.014	He	(c)	He	20
	Fuel bleed	Poppet	1.0	25.4	1130	7791	–	–	LH_2	Pneumatic bellows	He	120
	Augmented spark igniter	Poppet	0.5	12.7	911	6281	–	–	LOX	Pneumatic bellows	He	100
	Emergency vent	Poppet	0.25	6.35	1500	10343	0.015	0.007	GH_2	Flat-face-armature solenoid	NA	9
	Start tank discharge	Poppet	2.0	50.8	1500	10343	20.00	9.072	GH_2	Pneumatic piston	He	205
	Main oxidizer sequence	Cylindrical slide	0.25	6.35	400	2758	0.031	0.014	He	Actuated by MOV piston motion	NA	10
	Main fuel sequence	Poppet	0.25	6.35	400	2758	0.031	0.014	He	Actuated by MFV piston motion	NA	5
S-IVB System	LOX chilldown shutoff	Poppet	2.0	50.8	125	862	4.8	2.18	LOX	Pneumatic bellows	He	250
	Actuation control module (two 3-way valves)	Poppet	0.25	6.35	475	3275	0.03	0.014	He	Plunger solenoid	NA	150
	Oxidizer shutoff prevalve	Butterfly	10.0	254.0	60	414	386.0	175.09	LOX	Pneumatic piston	He	315
	Fuel shutoff prevalve	Butterfly	10.0	254.0	60	414	78.0	35.38	LH_2	Pneumatic piston	He	315
SE-7-1 APS (Ullage engine)	Oxidizer shutoff	Poppet	0.3125	7.94	195	1345	0.147	0.067	N_2O_4	Solenoid	NA	20
	Fuel shutoff	Poppet	0.3125	7.94	195	1345	0.116	0.053	MMH	Solenoid	NA	20
	Quad redundant bipropellant	Poppet	0.25	6.35	195	1345	0.311	0.141	N_2O_4	Solenoid	NA	20
		Poppet	0.25	6.35	195	1345	1.189	0.539	MMH	Solenoid	NA	20
Centaur RL 10 (Cluster of two engines)	Oxidizer pump inlet shutoff	Ball	2.5	63.5	60	414	29.3	13.29	LOX	Pneumatic bellows	He	17
	Fuel pump inlet shutoff	Ball	2.5	63.5	30	207	5.85	2.654	LH_2	Pneumatic bellows	He	17
	Mixture ratio	Poppet	1.5	38.1	600	4137	29.3	13.29	LOX	(a)	–	–
	Main fuel shutoff	Poppet	3.0	76.2	580	3999	5.85	2.654	LH_2	Pneumatic bellows	He	10
	Oxidizer fill and drain	Poppet	5.0	127.	30	207	–	–	LOX	Pneumatic piston	He	
	Fuel fill and drain	Poppet	5.0	127.	30	207	–	–	LH_2	Pneumatic piston	He	
8093 (Attitude control)	Propellant shutoff	Poppet	0.375	9.53	300	2069	0.0094	0.004	H_2O_2	Solenoid	NA	20

Table I. - Design Features of Representative Operational Valve Assemblies (concluded)

Vehicle and engine	Valve use	Valving element	Line size		Operating pressure		Flowrate		Service fluid	Actuator type	Actuator fluid	Response time, msec
			in.	mm	psi	kN/m^2	lb/sec	kg/sec				
Upperstage Systems (concluded)												
Transtage AJ10-138	Bipropellant	Poppet	1.75	44.45	150	1034	38.	17.2	N_2O_4	Hydraulic piston	A-50	400
		Poppet	1.75	44.45	150	1034	24.	10.9	A-50	Hydraulic piston	A-50	400
MR-3A (Attitude control)	Monopropellant (series redundant)	Poppet	0.25	6.35	360	2482	0.117	0.053	N_2H_4	Torquemotor flexure tube	NA	5
Satellite Systems												
Intelsat III Thruster	Monopropellant fuel shutoff	Dual poppet (series redundant)	0.25	6.35	600	4137	0.015	0.007	N_2H_4	Dual, redundant solenoid	NA	20.
Spacecraft Systems												
Gemini SE-6 (RCS)	Oxidizer shutoff	Poppet	0.1875	4.76	295	2034	0.0467	0.021	N_2O_4	Solenoid	NA	6.5
	Fuel shutoff	Poppet	0.1875	4.76	295	2034	0.0360	0.016	MMH	Solenoid	NA	6.5
SE-7 (OAMS)	Oxidizer shutoff	Poppet	0.3125	7.94	295	2034	0.158	0.072	N_2O_4	Solenoid	NA	20.
	Fuel shutoff	Poppet	0.3125	7.94	295	2034	0.131	0.059	MMH	Solenoid	NA	20.
Apollo Command Module SE-8 (RCS)	Oxidizer shutoff	Poppet	0.375	9.53	300	2069	0.230	0.104	N_2O_4	Solenoid	NA	8. (autocoil)
	Fuel shutoff	Poppet	0.375	9.53	300	2069	0.109	0.049	MMH	Solenoid	NA	16. (direct)
Apollo Service Module AJ10-137	Quad redundant bipropellant	Ball	2.00	50.8	225	1551	38.	17.2	N_2O_4	Pneumatic piston	GN_2	850.
		Ball	2.00	50.8	225	1551	24.	10.9	A-50	Pneumatic piston	GN_2	850.
R-4D (RCS)	Oxidizer shutoff	Poppet	0.3	7.6	170	1172	0.239	0.108	N_2O_4	Solenoid	NA	25.
	Fuel shutoff	Poppet	0.3	7.6	170	1172	0.118	0.054	A-50	Solenoid	NA	25.
Landing Craft Systems												
Lunar Excursion Module Descent Engine	Quad redundant bipropellant	Ball	2.0	50.8	222	1531	20. (max)	9.1 (max)	N_2O_4	Hydraulic piston	A-50	170.
		Ball	2.0	50.8	222	1531	12.6 (max)	5.72 (max)	A-50	Hydraulic piston	A-50	170.
	Oxidizer cavitating venturi	Pintle	2.0	50.8	222	1531	20. (max)	9.1 (max)	N_2O_4	Electric motor	NA	Throttling
	Fuel cavitating venturi	Pintle	1.75	44.45	222	1531	12.6 (max)	5.72 (max)	A-50	Electric motor	NA	Throttling
	Actuator isolation	Poppet	0.625	15.88	222	1531	–	–	A-50	Solenoid	NA	30.
Ascent Engine	Quad redundant bipropellant	Ball	1.175	29.85	190	1310	7.0	3.18	N_2O_4	Hydraulic piston	A-50	175.
		Ball	1.175	29.85	190	1310	4.3	1.95	A-50	Hydraulic piston	A-50	175.
	Actuator isolation	Poppet	0.375	9.53	190	1310	–	–	A-50	Solenoid	NA	30.
R-4D-2 (RCS)	Oxidizer shutoff	Poppet	0.3	7.6	180	1241	0.24	0.109	N_2O_4	Solenoid	NA	25.
	Fuel shutoff	Poppet	0.3	7.6	180	1241	0.12	0.054	A-50	Solenoid	NA	25.

Notes: MOV = main oxidizer valve; MFV = main fuel valve; GG = gas generator; HS = head suppression; PU = propellant utilization
GN_2 = gaseous nitrogen; A-50 = aerozine 50; NA = not applicable; GH_2 = gaseous hydrogen; He = helium
(a) Poppet is spring-loaded closed, and is opened by rising pump discharge pressure
(b) 0.4536 to 54.43 kg/sec
(c) Pneumatic diaphragm (Mylar)

S-IVB vehicle are used successfully in a restartable system. The main nonmetallic lip seals on the disk are a limiting factor in present butterfly valves, especially those of large diameter. Changes in physical properties after exposure to propellant and lack of dimensional stability of the seal have posed design problems. The integrity of the present butterfly lip seal at the high shutoff pressures of advanced propulsion systems with very high chamber pressures is unproved.

The ball valve has been used extensively in rocket engine systems. Although problems with seal wear have arisen, progress has been made in achieving adequate seal life with the simple nonretractable seal. Internal-redundant valve designs or common bipropellant valve linkages are simplified by the overtravel tolerance of the ball, which enables a positive seal to be achieved with a very generous angular tolerance on the ball. Also, design concepts that eliminate sliding parts in the valve assembly have been applied successfully in several operational valves. Such valves include the dc-torquemotor-operated valve with flexure tubes, pressure-actuated valves utilizing flexure disks, and solenoid-operated valves using flexure disks to support a flat-face armature. Integrated designs for actuator and valving unit, which utilize common housings for weight and envelope reduction, have been used successfully in large operational butterfly and ball valves.

The poppet valve and the ball valve are finding increasing use. A retractable-seal ball valve or a fixed seat and translating ball element offers the sealing features and high cycle life of the poppet with the flow characteristics of the ball. Such ball valves may be a requirement in future high-chamber-pressure rocket engine systems that are recoverable and reuseable.

2.1 VALVE SELECTION

Design of a valve assembly for use in a given propulsion system begins with tradeoff studies to select the valving unit type. This valve selection process is based on the analysis of the factors important in the proposed valve application and in the mission for which the propulsion system is being designed. Valve characteristics that influence selection for a given application include flow characteristics, differential pressure vs size, valve assembly weight, leakage, forces on the valving element under both static and dynamic conditions, compatibility of materials with working fluid, response characteristics, cycle life, and contamination sensitivity.

Throttling valves (e.g., the cavitating venturi valves on the Lunar Module descent engine), in addition to possessing the characteristics mentioned above, must exhibit the desired flow characteristic over the flow range being throttled and be capable of being accurately contoured. The definition of these characteristics for each valving unit type makes possible the systematic selection of the optimum unit for a set of specific propulsion-system requirements.

Factors that can influence the final selection to a greater degree than many of those listed are the design experience available on a given valving unit type and the proven concepts successfully utilized on previous propulsion systems. These somewhat intangible factors occasionally can weigh heavily in the final selection, particularly since costs can be better estimated and controlled when significant experience is available.

2.1.1 Flow Characteristics

The flow characteristics required of a valve depend on its use in the propulsion system. For propellant shutoff valves, the prime consideration is to achieve the required flow with the least system pressure loss while staying within valve envelope and weight requirements. For pilot valves and valves that route flow for engine sequencing functions, the prime consideration is the output at the design point rather than valve pressure drop. For throttling valves, the prime considerations are the relation between pressure drop and valving element stroke, accuracy of valving element contours, and flow characteristics over the flow range desired. Throttling valves are discussed separately in section 2.1.8.

For a propellant shutoff application, flow-resistance comparisons are utilized to establish the valve type most suited to the system requirements. Although flow-test data may be available on several specific valve designs, usually the data will be extrapolated. Data generated on similar valve types in industrial applications may be helpful. Such commercial data will use several of the more common coefficients to describe the loss in static head across the valve. These coefficients are considered sufficiently rigorous for the valve selection process, since flow testing of each candidate valve type usually is not possible. Resistance coefficient K [the reduction in static head expressed in units of velocity-head loss, i.e., $H_{loss} = K(v^2/2g)$] is presented in Table 7-4 of reference 3. The flow coefficient C_V, which is defined as the flow of water at 60° F in gallons per minute at a pressure drop of 1 psi across the valve, is shown for various valves in figure 1 (from sec. 3.8.4 of ref. 4). Other flow formulas and coefficients employed in valve sizing are described in section 3.8 of reference 4. Section 3.8.4 of reference 4 presents factors to be used when converting from one method to another (e.g., $C_V = 29.9\ D^2/\sqrt{K}$, where D is line diameter expressed in inches).

Section 7.9 of reference 3 discusses flow considerations for the design of small control valves and valves that route flow for engine sequencing functions. Output of these valves at the design point is based on the pressure and flow volume necessary to achieve the required actuator travel time of the valve controlled by the pilot.

Valving element types and their flow characteristics are shown in Table II together with the present size limits of operational flight-weight valves. Poppet valving units have a flow resistance greater than butterfly, ball, and blade valves; however, the poppet valve has a

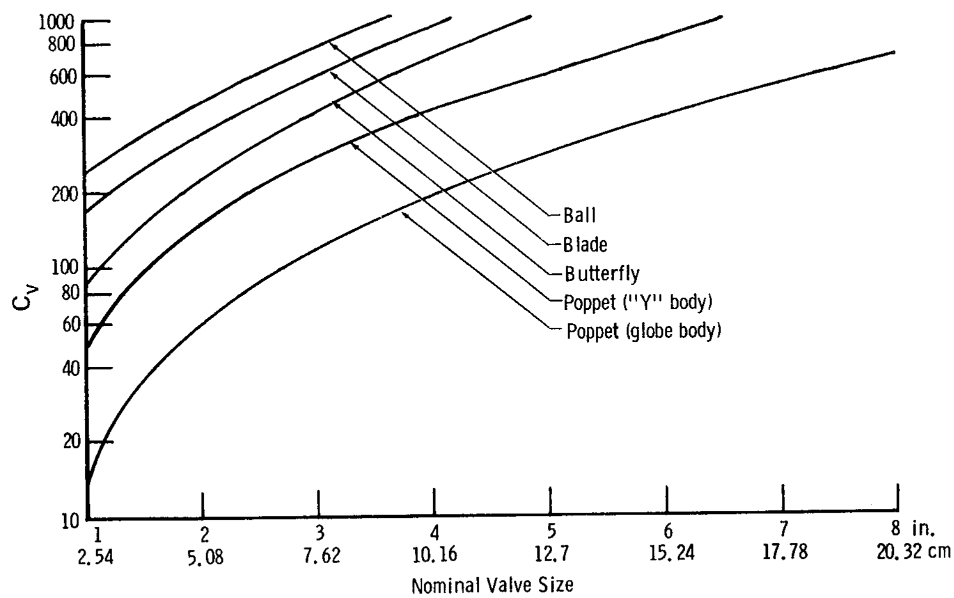


Figure 1. - Flow coefficient vs valve size, various types of valves (ref. 4, sec. 3.8.4.2).

number of distinct advantages such as low leakage, high cycle life, and the capability of being balanced. This combination of characteristics has resulted in selection of the poppet valve for shutoff applications ranging in size from the main propellant valves for the 1,522,000-lbf (6770 kN)[1]-thrust F-1 engine to the valves on the 93-lbf (414 N)-thrust SE-8 RCS engine. Various body styles such as angle, globe, Y-pattern, and in-line are employed with the poppet valving unit to integrate it into the flow system with the least total system pressure loss (sec. 5.2.5, ref. 4) and conformance to the available envelope.

Poppet valves selected for control and sequencing valve functions are usually multipassage valves, with drilled ports and intricate passageways. With these valves, flow-direction changes and associated pressure losses are less important than maintaining sufficient flow area throughout the valve. The flow area of such a small valve usually is calculated from the orifice equation, in which the discharge coefficient C_D is an empirical constant relating flow, flow-area geometry, and pressure drop. For three-way and four-way poppet valves, values for C_D range from 0.5 through 0.8 (refs. 4 and 5). This valve discharge coefficient is not the same as an actual orifice C_D, since the downstream pressure on a valve is measured at the valve outlet, not at the vena contracta. Butterfly valves are the predominant choice for thrust chamber main valves and propellant tank prevalves. With the disk rotated open, the flow path has only a slight change of direction and small associated pressure drop. The

[1]Parenthetical units here and elsewhere in the monograph are in the International System of Units (SI units). See Mechtly, E. A.: The International System of Units. Physical Constants and Conversion Factors. Second revision, NASA SP-7012, 1973.

TABLE II. – Flow and Envelope Characteristics of Various Types of Valving Units

Valving unit type	Flow Coefficient[a], C_V	Size range of present valves		Principal advantages	Principal disadvantages
		in.	cm		
Poppet	60 to 70	0.25 to 8.0	0.64 to 20.32	Short stroke opens large flow area; 90-degree angle valve can be used in place of elbow; simple design	Large L/D housing; low differential pressure can be achieved only by increasing poppet diameter and therefore housing size and by costly contouring of flow passage
Butterfly	333[b]; 154[c]	2.0 to 8.0	5.08 to 20.32	Short face-to-face dimension; low differential pressure at optimum size and pressure range	Poor for line sizes less than 2 in. (5.1 cm) and for high pressures where a thick disk and shaft reduce flow area
Ball	440	1.0 to 17.0	2.54 to 43.18	Full line flow with no obstructions in full-ported valve; structurally good for high-pressure service without sacrificing flow area	Body dimensions are large; valving element mass is large
Blade	310	0.75 to 1.0	1.9 to 2.54	Full line opening with no obstructions; shortest face-to-face dimension	Large body dimension in plane plane normal to axis of flow

[a] 2-in. (5.1 cm) valve (ref. 4, sec. 3.8.4.2)

[b] $\frac{\text{Disk thickness}}{\text{Disk diameter}} = 0.07$

[c] $\frac{\text{Disk thickness}}{\text{Disk diameter}} = 0.35$

valve has an optimum size and pressure range. In small lines (<2 in. [5.1 cm]), the rotating disk occupies a large percentage of the flow area, negating the low-pressure-drop characteristics of the valve. At high pressures, the thick disk and large shaft required to withstand full line differential pressure adversely affects the flow coefficient.

The ball valve is used on the gas generator for the F-1 engine, for the prevalves and fill and drain valves for the Saturn S-1C propellant tanks, and for engine main valves in the Apollo Service Module, LM Descent, and LM Ascent propulsion systems. The flow passage through the ball element is essentially unobstructed on full-ported ball valves; however, sealing surfaces and transition regions create flow disturbances. The ball valve maintains its flow coefficient for high-pressure service, because the ball can be designed to withstand the full pressure drop at shutoff without sacrificing flow area. In valves located upstream of engine pumps, where flow disturbances can cause pump performance to be affected, the ball valve has been utilized to minimize downstream flow disturbances; the ball valve provides the least flow disturbance and is ideally suited for such applications. A variation of the ball valve element is the visor. The visor design reduces weight and valve envelope by cutting away half of the ball and using only a spherical segment. Visor designs have been successfully used for the prevalves on the Saturn S-1C tanks.

Blade valves are in limited use in state-of-the-art propulsion systems. The flow area of the valve is essentially unobstructed, with only the slot in which the blade moves creating some disturbances. The blade valving unit has the shortest face-to-face dimension or installed length requirement of all valve types. Blade valves were used as shutoff valves on the MA-5 and MB-3 gas generators.

Sleeve valves have limited application on operational vehicles. On an early vehicle, the Redstone, a reciprocating sleeve valve was selected for the main fuel valve of the thrust chamber. More recently, the sleeve valve type was initially selected for the thrust-chamber main valves on the M-1 engine; however, development problems concerned with seal leakage around the sleeve (ref. 6) required replacement with a poppet-type valve. The pressure drop through the valve is determined by the area opened as the sleeve moves to expose slots. On the rotating sleeve element, the cylinder moves to align the slots and opens the flow passage. The sleeve valve presently is used only for throttling (sec. 2.1.8).

The cylindrical slide or piston valve, a simple piston device, currently is used as the engine-sequencing control valves on the Titan III engines and in the J-2 engine pressure-ladder sequence. The valve is effective for low flows, where pressure drop is not a prime factor in selection. The spool valve is similar to the cylindrical slide; however, in most cases the valve is ported for routing large flows in hydraulic control systems. The four-way valve on the F-1 engine is an example of the spool valve used for flow-routing purposes.

A plug valving unit with a wedging action is used on normally open explosive valves. In the open position, the flow path is essentially unobstructed. Such valves have been used in the small propellant and pressurant flow systems for spacecraft.

After a particular valve type is selected, more detailed considerations must be employed to ensure that the valve will function over the full range of operating conditions. When available flow data are not adequate for reliable evaluation, flow testing is necessary. Flow passage shaping is important in achieving the lowest pressure drop and the least disturbance to downstream sections of the system. In the case of thrust-chamber main valves or prevalves immediately upstream of the pump inlets, downstream disturbances are particularly critical. Streamlining and shaping of the flow passage are discussed in section 2.2.1.

Constancy or repeatability of flow characteristics from valve to valve depends on machining and casting tolerances and on assembly tolerances. In large valves, the changes in flow characteristic caused by different stackups of these tolerances usually cause negligible change in pressure drop. However, in small valves, the effects of tolerance stackup differences from valve to valve are more pronounced, and dimensional changes have significantly altered flow characteristics and thereby affected propulsion system performance.

2.1.2 Leakage Characteristics

The capability of a valve to achieve complete shutoff of fluid flow is a prime factor in selection of a valve for propellant or pneumatic systems. Leakage can occur internally past the valving element or externally through dynamic or static seals in the housing. Leakage of fluid past the internal or external seals has resulted in serious problems:

(1) Valve sealing surfaces were eroded, and the seal failed completely.

(2) Either the pressurant or propellant was prematurely depleted, and the programmed mission duty cycle could not be completed.

(3) Downstream plumbing was clogged with frozen propellant when the propellant expanded to a pressure below the triple point pressure in a flow system exposed to the hard vacuum of space (evaporative freezing).

(4) Hard start of the engine occurred because incorrect propellant lead caused formation of explosive mixtures.

(5) Portions of the system or vehicle were damaged by leaking corrosive propellants or by fire and explosion of flammable propellants that leaked into confined spaces of interstages and engine compartments.

(6) Personnel were exposed to hazards from leaking toxic fluids or from fire and explosion due to flammable fuels reacting with air or with the oxidizer.

(7) Diffusion of propellant vapors in vicinity of the instrumentation interfered with gas measurement experiments on board the spacecraft.

(8) In spacecraft, proper attitude of the spacecraft and station keeping could not be maintained and, in extreme cases, roll or spin rates could not be controlled, because of the thrust generated by leaking propellant.

The consequences of leakage are assessed for each particular valve application and the intended mission. The valve design leakage value is based on past experience with similar type valves and is established a safe margin below the maximum tolerable system leakage. The pressure differential across the sealing surface of the valve element may change as upstream pressure increases from tankhead to pump discharge and ambient pressure decreases from 760 mm (101.3 kN/m^2) to 1×10^{-8} mm Hg (1.33 $\mu N/m^2$). If extended vehicle coast periods present the most critical conditions, then the differential between tank ullage pressure and ambient pressure may be the most realistic pressure differential to use in valve leakage assessments. Table III lists permissible leakage rates in some representative operational valves.

A primary factor in the leakage rate of any valve design is the nature of the materials composing the valve sealing surfaces. Two kinds of surfaces are involved: hard and soft. For poppet valves, the term "hard-on-hard" designates a valve with hard metallic surface on both poppet and seat; the term "hard-on-soft" designates a valve with a hard poppet and a plastic or elastomeric seat, or one with a hard seat and a plastic or elastomeric surface on the poppet. (For further details, see ref. 2).

For hard-on-hard valves, equations found in reference 7 may be used to predict valve leakage. For hard-on-soft valves, calculation of expected leakage rates using laminar-flow equations is not justified because the flow channel cannot be described adequately; experimental leak data from similar seat design is necessary to predict the leakage that could be expected in a new valve design. The use of experimental data to predict leakage of valves with soft seats applies not only to poppet valves but to all valving units treated in the monograph.

The poppet valve is the best selection for a valve with low internal leakage. Either soft or hard seats can be employed, the choice depending on the reactivity of the fluid handled. Poppet stems can be hermetically sealed for zero internal leakage by using bellows. Scrubbing and sliding of sealing surfaces can be minimized in the poppet valving unit.

In most applications, the butterfly valving unit employs soft nonmetallic lip seals to achieve tight shutoff around the disk. Exceptions to this, however, are the prevalves for the Titan III

TABLE III. — Permissible Leakage Rates in Some Representative Operational Valves

Stage or engine system	Valve type and use	Service fluid	Seal type and material	Sealing diameter in.	Sealing diameter mm	Leak test pressure psig	Leak test pressure kN/m^2	Leakage rate (room temp.) scim	Leakage rate (room temp.) scc/min	Gas
F-1	Poppet, MOV	LOX	Captured Teflon poppet nose seal	8.0	203.2	80	552	56	917	N_2
SE-8	Poppet, propellant shutoff	N_2O_4	Captured Teflon seat seal	0.150	3.81	300	2069	$2x10^{-4}$	0.0033	N_2
J-2	Butterfly, MOV	LOX	Kel-F lip seal	4.0	101.6	500	3448	5	82	He
J-2S	Butterfly, MOV	LOX	Kel-F lip seal	4.0	101.6	500	3448	3	49	He
S-IC	Ball (visor), prevalve	RP-1	Rubber spherical seat	12.0	304.8	54	372	20	328	N_2
S-II	Butterfly, prevalve	LOX	Kel-F lip seal	8.0	203.2	50	345	450	7376	He
LMAE	Ball, shutoff	N_2O_4	Teflon ball seal	1.0	25.4	250	1724	0.01	0.164	N_2
J-2S	Ball, idle mode	LH_2	Kel-F ball seal	1.6	40.6	500	3448	3	49	He
MA-5	Blade, GG bipropellant	LOX	Machined Kel-F ring	1.0	25.4	500	3448	10	164	N_2
J-2	Poppet, 4-way pneumatic package	He	Flexible metal disk	0.50	12.7	400	2758	5	82	He
Mariner	Explosive-driven ram	N_2H_4	NA	0.25	6.35	300	2069	$6x10^{-5}$	$9.8x10^{-4}$	He

booster engines, where no leakage can be tolerated because of the toxic nature of the propellants and because long-term exposure of soft seals in the engine main valves results in reduction of seal physical strength. A thin metal diaphragm, welded circumferentially around the valve, is sandwiched between the disk halves to achieve a hermetic seal. When the valve actuates, the diaphragm is ruptured. Such metallic gate seals are not reusable and are "one-shot" designs. Metal-to-metal seals for butterfly valving elements have been designed, but none are in present use on operational vehicles.

The ball valve is used for propellant shutoff in several of the present operational upper stages and manned spacecraft. All of the present valves employ soft nonmetallic ball seals. The ball valve element can employ a single seal or double seals for redundancy. The visor variation of the ball valve finds application in low-pressure shutoff; the spherical seat can achieve tight shutoff.

Blade valves are employed primarily for propellant shutoff. Nonmetallic machined rings provide the main seal for the blade.

Sleeve valves exhibit poor sealing properties, and such valves are not used for shutoff applications. The valve finds application in engine sequencing or throttling functions where low internal leakage is not a prime selection factor.

The cylindrical slide valve is a simple device selected for engine sequencing controls where low leakage is not a prime factor. Close fit or nonmetallic lip seals or O-rings are employed to control leakage. With this valve, provisions are made to handle leakage so that it does not interfere with the sequencing function.

2.1.3 Valving Unit Forces

The forces that act on the valving unit under nonflow static pressure conditions, under flow conditions, and under surge pressures experienced at shutoff are important factors in valve selection. The flow coefficient and the envelope and weight of a particular valving unit can be affected adversely by the required strengthening of the valving element, by the use of larger shafts and bearings, and by the necessary increase in the strength of the housing to withstand the forces that result from increased pressures. As the force required to actuate the valving unit increases, the valve design often incorporates a balance chamber. Balance-chamber designs not only reduce actuator force and total power requirements, but also can reduce the integrated valve and actuator envelope. Valving units such as the poppet and the sleeve are capable of utilizing the balance-chamber concept and thus can offer advantages over butterfly, ball, and blade designs, which are considered unbalanced.

The balance-chamber design for the main propellant valve on the F-1 engine placed severe requirements on the dynamic seal. The large diameter of the thrust chamber, high service pressure, and thermal transients and surface pressures at closure resulted in numerous seal failures. Propellant leakage past the balance-piston seal is additive to leakage past the primary valving unit seal and therefore must be limited. Failures due to seal fracture were corrected by ensuring adequate thermal conditioning prior to valve operation and by changes in tolerances to provide additional clearance, since the seal was found to chill to liquid-oxygen temperatures more rapidly than surrounding parts of the valve. Maintaining adequate sealing forces on the primary seal also posed early design problems on the F-1 engine main valve. Decreases in the static pressure head in the propellant lines to the valve reduced the net sealing force and caused the valve to leak. In order to ensure tight shutoff, a separate hydraulic pump in the ground support equipment was used to maintain 1500 psi (10.3 MN/m^2) in the system.

Sleeve valves originally were considered for main valves on the M-1 engine; however, use of the sleeve valve for a tight shutoff of this type proved extremely difficult because of leakage past the sleeve seals. Later designs of the M-1 main valves utilized the balanced-poppet concept.

The balance-chamber concept also offers advantages in throttling valves, because the total power required to control the valve can thus be reduced. Analysis of balancing methods for flow-control valves can be found in section VII of reference 8. Figure 2 from reference 8 shows how the forces on the poppet can be varied by balance-chamber design.

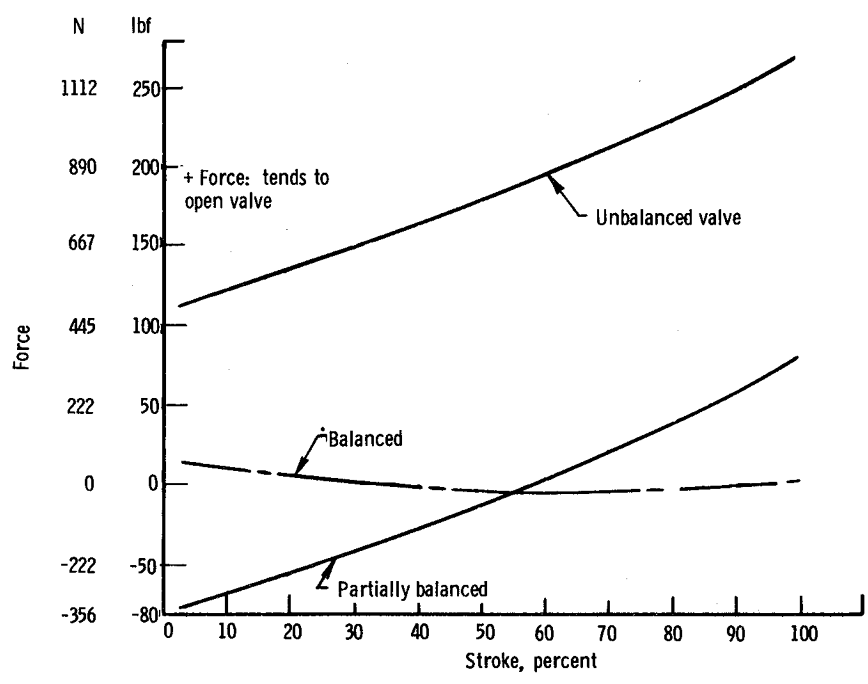


Figure 2. - Force vs stroke relationship for poppet valving element in unbalanced, partially balanced, and balanced designs.

An analysis of balancing flow forces in high-pressure shutoff valves is presented in reference 9.

On butterfly valves, the forces resulting from high service pressures require thick disks and large shafts, both of which adversely affect the flow coefficient. Also, the butterfly valving unit has a dynamic torque imbalance (ref. 4, sec. 6.2.3.5). However, present operational booster engines operating at moderate pressures utilize butterfly valving units for the thrust-chamber main valves. At moderate pressures, the valve offers a smaller envelope than other valving unit types.

Ball valving units exhibit torque imbalance characteristics similar to those of the butterfly valving unit. However, the ball design is capable of withstanding high pressures without reducing flow area. Ball seal loads at high pressures and large ball sizes result in high friction loads and hence increased opening torques.

The blade valve generally is not used for high pressures or for line sizes larger than 1 in. (2.5 cm), because the initial torque on the blade can be very high as a result of pressure imbalance and resulting high seal friction loads.

Spool valves are selected for hydraulic power units (e.g., the F-1 engine 4-way valve) to direct fluid for valve control. Flow forces on the spool can be predicted by methods given in references 10 and 11. The flow forces on the spool valve element are of particular concern when the valve is used in a servo control loop. Hydraulic control valves are discussed in the design criteria monograph "Liquid Rocket Actuators and Operators" (ref. 12).

2.1.4 Valve Material/Fluid Compatibility

Materials for the valving element and sealing surfaces must be compatible with the working fluid for extended periods of time, at extremes of temperature, under impact loads, and under dynamic flow conditions. With advanced high-energy propellants such as chlorine trifluoride or fluorine, nonmetallic materials usually cannot be used in the valve. In some cases, metallic materials that are compatible with the pure liquid are severely attacked if trace impurities are present. Materials subject to stress corrosion are unacceptable in any part of a valve, because slight seal leakage can create a corrosive environment on a highly stressed part.

Poppet valves have been used when compatibility problems dictated hard seats. Excellent sealing and leakage characteristics can be achieved with metal-poppet/metal-seat designs, and the short-stroke feature of the poppet allows the selection of metallic bellows so that the use of nonmetallic materials for the stem seal can be avoided.

Nonmetallic materials used for some valve element seals are shown in column 4 of Table III. A more extensive listing is found in Table I of reference 2. Nonmetallic materials for main-gate lip seals on butterfly valves have posed problems in nitrogen tetroxide systems. The use of Kel-F for the butterfly disk lip seal for the thrust-chamber valves on the LR-87-AJ-5 and the LR-91-AJ-5 engines (Titan III first and second stage, respectively) resulted in shortened life for the valve assembly when the seal was exposed to N_2O_4 oxidizer; seal life after exposure is 30 days unless the seal is decontaminated. The useful service life of exposed seals has been extended to 18 months by proper decontamination of the valve and seal.

Nonmetallic materials for shaft and piston lip seals have posed compatibility problems. Although no valve failures have been attributed to Mylar reacting with liquid oxygen, the use of Mylar with liquid oxygen has been discontinued, because impact sensitivity tests have shown that the material is sensitive under severe impact conditions. Kel-F has replaced Mylar as seal material in liquid-oxygen systems.

2.1.5 Response Characteristics

Response requirements for the valve are based on the particular control-system requirements. It is important that required response times be realistic, because actuator size and power expenditures increase when rapid response is a design requirement. Also, rapid actuation can cause high rubbing velocities and reduce seal life, and when the parts of the valve set in motion must be stopped, high levels of impact energy can cause component failure or distortion and shorten valve life.

In small RCS engines, the control valves are operated by electrical sequence so that extremely small impulse bits can be generated. In larger engines where rapid response may not be necessary, valves are opened or closed by a pressure-ladder sequence or by an electrical sequence. The operating time is part of the start sequence during which propellants must be metered into the thrust chamber or combustor. On stage prevalves, which are normally open valves, valve opening time is not critical, but rapid closing is a requirement in stage hot firings or as a backup for engine shutdown should a malfunction occur. The opening and closing times of state-of-the-art valves used in some representative operational systems are listed in Table IV.

The poppet valve with its short-stroke capability provides a good mechanism for obtaining fast response. As shown in Table IV, response times for the small poppet valves used in SE-5 engine are on the order of 6 msec to open, 3 msec to close. In these small valves, rapid response can be achieved without incurring excessive seat stresses; however, as valve size increases, seat stresses are higher, and design precautions must be taken to achieve reasonable cycle life.

TABLE IV. – Response Times for Some Representative Operational Valves

Stage or Engine system	Valve type and use	Line size		Actuator type	Valve response time, msec	
		in.	cm		Open	Close
J-2	Butterfly, MOV	4	10.2	Pneumatic cylinder	50	50
F-1	Poppet, MOV	8	20.3	Hydraulic cylinder	480	500
J-2S	Ball, idle mode	1.5	3.8	Pneumatic cylinder	100	100
S-II	Butterfly, prevalve	8	20.3	Pneumatic bellows	N.O.*	1000
SE-5	Poppet, MFV or MOV	0.5	1.3	Solenoid	6	3
F-1	Ball, GG bipropellant	1.5	3.8	Hydraulic cylinder (propellant actuated)	175	175
LMAE	Ball, bipropellant (quad redundant)	1	2.5	Hydraulic cylinder (propellant actuated)	175	150
MB-3	Blade, GG bipropellant	1	2.5	Pneumatic cylinder	100	100

* Normally open

In comparison with poppet valves, butterfly valving units normally require longer operating strokes and heavier actuators. In ball valves, weight of the sphere, dynamic forces, sealing loads, and the stroke required to achieve a 90° rotation of the ball result in large actuators and make rapid response difficult to achieve. Blade valving units have good response characteristics; depending on the particular geometry of the blade, the degree of rotation required to open such a valving unit usually is less than that for the butterfly and ball designs. Rotary sleeve valving units usually require less rotation than other rotary valve types. Spool valve operating times are dependent on sliding friction and the fluid force that must be overcome as the spool slides along the bore. These valves are capable of rapid actuation, and precautions may be necessary to avoid damage to the spool from impact with the ends of the valve bore.

2.1.6 Cycle Life

Cycle life is the number of times a particular valve may be operated and still perform satisfactorily. Although inadequate cycle life may result from the complete failure of some particular component of the valve, in most cases valve failure is described in terms of excessive internal leakage across the valving element seal. Before such failure occurs, the leakage across the valving element seal usually goes through a period where leakage decreases with number of cycles (a phase thought of as a "run-in" or "wear-in" process) followed by an increase of leakage with number of cycles (conversely thought of as a "wear-out" process) that ends in leakage exceeding the allowable maximum.

Cycle life can be predicted accurately only for one-cycle valves such as the explosive-actuated types. Other valve types may be exposed to numerous cycles without propellant (dry mode) and numerous cycles with service or test fluid (wet mode) in the various functional tests required prior to the final mission duty cycle. Pneumatic and hydraulic control-system valves in particular may accumulate long periods of operation under pressure as checkouts are performed on other components of the propulsion system. In addition to the total number of cycles, the rate of cycling is an important factor. Rapid dry cycling has caused damage to seats and seals. Long periods of energization of solenoid-actuated valves can increase temperatures above normal service or mission requirements, causing possible degradation of valve seat and seal materials. Storable-propellant systems using corrosive fluids must be flushed and decontaminated after exposure to prevent deterioration of software and corrosive attack on metallic materials in the valve. Compatibility of valve materials with the service fluid is a prime factor in cycle life, because cycle life is directly affected by any deterioration of mechanical properties.

Poppet valves have been employed where high cycle life is required. Valves used in reaction control systems where 100 000 cycles may be required are exclusively poppet valves, because with proper design little or no seat scrubbing will occur. However, although a small

(1/4 to 1/2 in. [6 to 13 mm]) well-designed poppet-type valve may be capable of thousands of cycles, as the valve size increases, impact-energy levels increase, higher stresses are imposed on seating material, scrubbing action may increase, and the length of sealing surface is greater. As a result, extended cycle life is more difficult to achieve in poppet valves larger than 1/2 in. (13 mm).

The inherent sliding or scrubbing action in butterfly disk lip seals, ball valve seals, blade valve seals, and sleeve valve seals shortens the cycle life of such valving units. Retractable seal designs have been used on ball valves to eliminate scrubbing of the seal during valve motion. On the 17-in. (43.2 cm) ball (visor) prevalve on the S-1C vehicle, adequate cycle life was achieved by using a retractable ball seal.

The following cycle lives are representative of some present operational valves:

J-2S butterfly:	30 engine firings; 3750 seconds mainstage; and 300 dry checkout cycles
J-2S ball:	30 engine firings; 3750 seconds mainstage; and 300 dry checkout cycles
MB-3 blade:	engine acceptance firings plus 100 checkout cycles

2.1.7 Contamination Tolerance

The presence of contamination in fluid systems is a well-established fact. Particles in the service fluid can damage sealing surfaces, jam close tolerance fits, distort or nick lip seals, and result in premature wearout of a valve. Especially destructive are particles in a gaseous flow medium, because flow across sealing surfaces can reach sonic velocity and particles will be accelerated to high velocities; deep scratches may be made on seats of the valve and lead to excessive leakage. Particles may also be trapped or embedded upon valve closing and cause progressive deterioration of the sealing surface. Problems also arise when the stroke of the poppet valving element is not sufficient to allow passage of the largest system contaminant. If contamination levels are not realistic, the valving unit design may be sensitive to contamination.

Filters can be installed upstream of valves in some applications, but such precautions may not be totally effective, because this location in the system does not protect a valve from particles generated in the system between the filter and the valve. Valving element motion that results in a wiping action can be beneficial, since it tends to clean the contact surfaces. As a result, butterfly and ball valving elements may exhibit greater tolerance and may be preferred when system contamination levels are high.

The poppet valving unit can maintain its flow characteristic over a wide flow range and thus exhibits a high turndown ratio. The poppet valving unit can achieve a combined throttling and shutoff valve function. The poppet valving element may be balanced to reduce actuator force requirements. The poppet or plug can have a lower pressure drop in the full-flow position than can the cavitating venturi valve.

Needle valves can throttle very low flowrates and often are used in line sizes less than 1 in. (2.5 cm). The valving element is essentially a poppet tvpe with a large tapered plug to provide the fineness of control required in small lines with associated low flows. Complete shutoff can also be achieved. Needle-type bipropellant valves with bodies integral with the thrust-chamber injector have been developed for flow control on attitude control engines, but so far these valves have not been operational. In these designs, the shutoff function is separated from flow control, and orifices are used to control propellant flowrate.

The butterfly valve has been used extensively for throttling propellants and hot gases. Reference 17 and section 6.2.3.1 of reference 4 present flow characteristics of the butterfly valving element. The butterfly valve has an equal-percentage characteristic for the first 50 percent of valve element travel and a linear characteristic for the remaining portion. The bore of the valve can be varied to achieve the desired characteristic; however, such machine profiling is costly, and close tolerances are difficult to maintain. The valving element is difficult to balance, and the butterfly is considered an unbalanced valve. Because the torque to open and close the valve varies with position, careful consideration must be given to actuator selection. Butterfly valves are used on the propellant utilization (PU) and head suppression (HS) valves on the MA-5 engine system, on the oxidizer turbine bypass valve (OTBV) on the J-2 engine, and on the hot-gas tapoff valve on the J-2S engine. Advantages of the valve are its adaptability to a directly linked electrical motor drive and low pressure drop in the full-open position.

The ball valve is suitable for throttling control in propulsion systems; however, it is not used in any present operational system. The characteristics of ball valves for throttling applications are presented in reference 18. The ball valving unit has a modified linear flow-characteristic curve. By special contouring of the ball, other flow characteristics similar to those of a shaped plug of a poppet throttling valve can be approached closely. The design is considered unbalanced, however, and actuation force greater than that for a balanced poppet is required.

The rotating blade valve offers a simple means of throttling a flow stream with a few moving parts. The flat seats and valving element blade are easily manufactured. The valve is designed for low-pressure service and is normally open when not throttling. The blade valve characteristic curve is modified linear.

A sliding blade or gate valve was used successfully for propellant utilization in the oxidizer system on the AJ10-137 engine. This valve type is not used widely because its effectiveness is limited to low-pressure systems. The sliding blade or gate valve characteristic curve is modified linear.

A rotary sleeve valve is used in the propellant utilization system of the J-2 engine. The desired throttling characteristics are achieved by rotation of the slotted inner cylinder, which varies the flow area. The characteristic curve for the rotary sleeve valve is modified linear. The valve can be balanced to reduce actuator force requirements.

2.2 MAJOR DESIGN PARAMETERS

After a valving unit type for a given control function has been selected, additional tradeoff studies are initiated to integrate the valve into the propulsion system. A detailed analysis of valve pressure drop is accomplished so that (1) passage shapes can be defined, (2) the basic valve envelope can be established, and (3) the orientation of the valve assembly in the available engine or vehicle envelope can be established to minimize total system pressure losses and downstream flow disturbances. If system reliability dictates redundancy, then an enlarged valve envelope that includes an additional valving element integrated into a redundant valve assembly may be required. The actuator selection based on the force required to achieve the specified valve response time is needed to establish the actuator envelope. In order to size the actuator, accurate estimates of the dynamic forces on the valving element and of the friction forces that are opposing motion are made. As part of the actuator selection phase, an analysis of the fail-safe mode for the system is performed to assess the preferred position for the valving element insofar as it affects the actuator selection. Repeatable valve actuation is critical for reliable propulsion system operation, and a thorough analysis of valve timing is performed.

2.2.1 Flow-Passage Shape

The flow coefficients generally associated with various valve types were presented in table II. However, after the valving element type has been selected and the layout of the valve within the confines of the available envelope is completed, more accurate analysis of pressure losses in the flow passage is required. Various methods are used to establish the pressure losses through the valve; references 19 and 20 describe several techniques. Prototype flow tests are made to verify the calculations (ref. 21).

2.2.1.1 SHUTOFF VALVES

To obtain the minimum pressure drop, various techniques are used to smooth out the flow passage to avoid sudden enlargements and sudden contractions that result in turbulence in the passage. Often the orientation of the valve in the duct may affect downstream turbulence. During early J-2 engine development testing, it was found possible to reduce the total drop through a section of duct by rotating the thrust-chamber butterfly valve; symmetrical bolt-hole circles enabled the valve to be reoriented in the available engine envelope without modification. In general, however, the following techniques are used to reduce pressure drop in the flow passage in butterfly, ball, and poppet valves.

2.2.1.1.1 Butterfly Valve

Sleeves are inserted within the valve to prevent sudden changes in flow cross section. The passage just upstream of the main-disk lip seal usually does not match the diameter of the mating upstream flow duct, because of the clearances required for the lip-seal installation. Integral lip-seal retainers and flow sleeves have been used in this area.

The area of the main disk bearings may also cause sudden enlargements or contractions and protuberances in the flow stream. Sleeves ensure a smooth transition region in this area. Separate idler and drive shafts also provide for a smoother flow section by avoiding the thick disk required by a one-piece shaft.

2.2.1.1.2 Ball Valve

Ball-valve flow passages can be essentially unobstructed if full porting of the ball is employed. To avoid producing turbulence by sudden enlargements and contractions in the ball seal area, flow straighteners are used. Their exact design depends on whether the ball seals are loaded by helical springs, Belleville springs, or bellows. Balls can be machined or fabricated. Turbulence from hollow balls may be reduced by use of a flow tube. Ball valves can be fabricated with reduced ball size if flow passages are shaped as venturi sections with smooth transitions for maximum pressure recovery. In addition to straightthrough designs such as those used in the RL10 engine ball valves and the AJ-10-137 engine redundant ball designs, ball passages can be contoured to obtain turns up to 90°. Such ball valves could be termed selector valves and are used for flow routing. The F-1 engine checkout valve utilizes this design feature to provide a low-pressure-drop three-way valve for routing hydraulic flow.

2.2.1.1.3 Poppet Valve

The shaping of the flow passage in poppet-type valves is a function of the basic body type that is selected; four body types are generally recognized (sec. 5.2.5, ref. 4). The system plumbing often will dictate the body type, because if an elbow is required the pressure drop can be utilized as part of the angle valve configuration. If the flow section is straight, other body types may be utilized. Wholly or partially machined castings or forgings generally are preferred in angle, Y-pattern, globe, or in-line poppet valve bodies in propellant service, because (1) the flow sections can be shaped to provide smoother transitions and (2) abrupt changes in direction that create turbulence and increase pressure drop in liquid propellant feed systems can be reduced.

In pneumatic control systems, poppet valves with drilled passages are utilized, since such valves are not required to be high-flow designs. Shaping to reduce turbulence in this type of valve is not a strict design objective; maintaining uniform flow area through the intricate passageways is the main consideration. Turbulence can be reduced by contouring either the tail or nose piece of the poppet element, the choice depending on flow direction. Reference 22 discusses such shaping and its effect on pressure drop.

2.2.1.2 THROTTLING VALVES

For throttling applications with the noncavitating valve, flow-passage geometry has major effects on accuracy of flow control. Pressure recovery is not desirable in the noncavitating throttle valve, and for control accuracy the largest pressure drop should occur across the valve throat. To minimize inlet and outlet losses, a flow-passage design such as the flow-to-open plug (fig. 4) is utilized. This design provides, downstream of the throat, a plenum or dumping chamber with a flow area at least six times the throat area at full flow, so that all the velocity head is lost after the fluid passes the throat. Such a design allows more accurate prediction of flowrate versus stroke, since the pressure at the throat equals the dumping-chamber pressure; this condition fixes the pressure coefficient used in the equation for incompressible flow and makes the weight flowrate solely a function of the throat area. A converging inlet configuration is used to ensure a uniform velocity profile at the throat. Reference 8 presents an analysis of pressure losses through several candidate throttling valve configurations. For cavitating venturi valves, flow-passage geometry consists of a straight length of inlet line with a converging section for establishing a uniform velocity profile at the throat, and a straight flow path to a downstream diffuser section after the throat to achieve maximum pressure recovery.

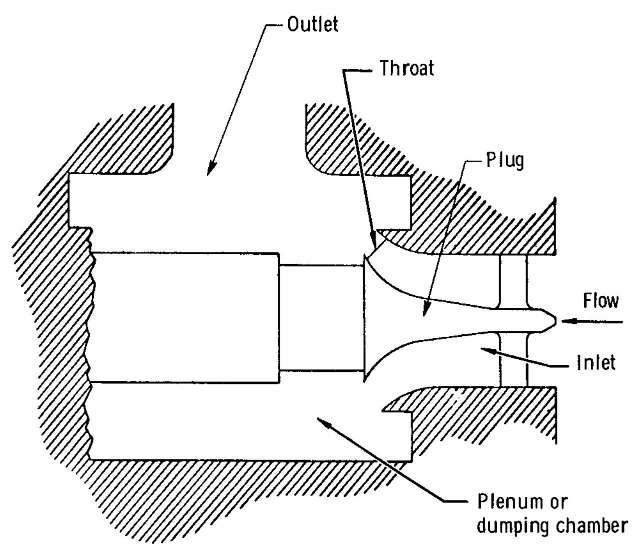


Figure 4. - Schematic of flow passage in noncavitating valve with flow-to-open plug.

2.2.2 Redundancy

To achieve a high degree of reliability in a spacecraft propulsion system, parallel systems sometimes are employed to provide a backup should trouble develop in one system. This type of backup exists on the SE-8 engine systems on the Apollo Command Module, where two separate reaction control systems have been incorporated. When weight restrictions do not allow a complete backup system, redundant components are utilized to achieve increased reliability. State-of-the-art valves utilizing series-parallel flow-circuit redundancy are in operational use on the AJ10-137, LMDE, and LMAE.

Redundant design to develop the configuration offering the greatest reliability requires a thorough analysis of probable failure modes. The redundancy is carried throughout the system, including valves and seals (fig. 5) and electrical components. Final steps in the design of a redundant configuration are to select proper actuators and integrate them into the common valve bodies that house the valving units. Valving elements with overtravel tolerance are more easily integrated into redundant designs, because linkage tolerances may be relaxed and adjustments to ensure tight shutoff of all joined valves are minimized. Figure 6 shows schematically the eight mechanically linked ball valves utilized on the LMAE redundant-valve package.

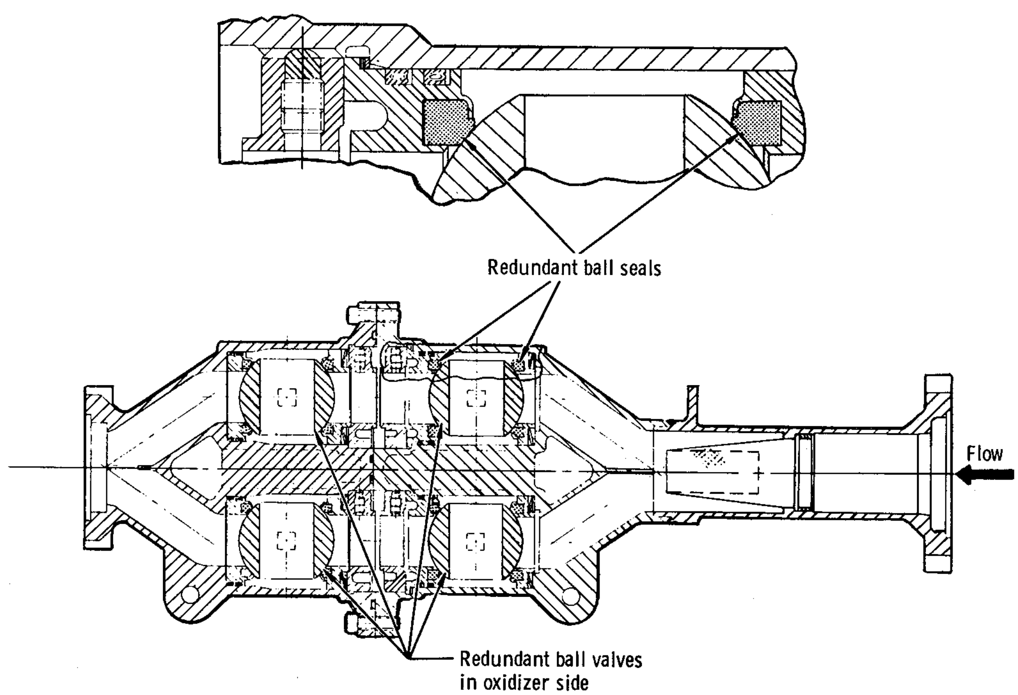


Figure 5. - Cross-section drawing of redundant ball seals and ball valves in the feed system for the Lunar Module Ascent Engine.

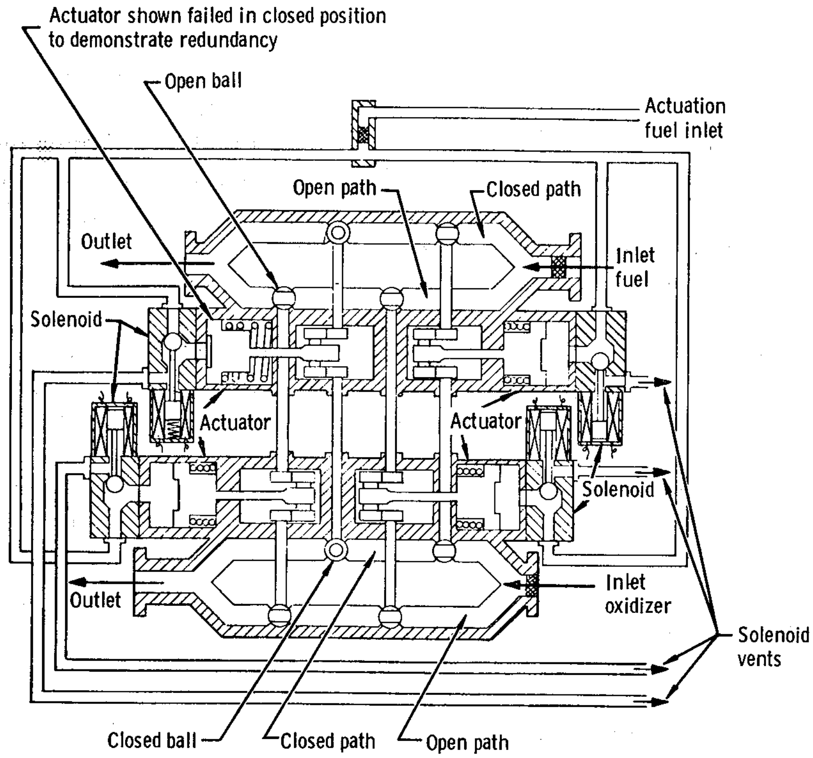


Figure 6. - Schematic of redundant-valve package in feed system for the Lunar Module Ascent Engine.

2.2.3 Fail-Safe Mode

The particular control-system function in the propulsion system will dictate whether a valve should fail in the open, closed or intermediate position if electrical power or control pressure is lost. A thorough analysis of possible failure modes and malfunction conditions of the propulsion system and control system is required to establish the safe mode. Mechanisms to latch and lock the valve in position can be part of the fail-safe provisions for ground static test of the propulsion system of the stage.

The term "fail-safe" may imply merely that the logic of the control system is to move the valve element to the desired position using normal actuation modes. Usually the desired position, should electrical power or control pressure be lost, is achieved by using a bias spring in the actuator to provide a normally open or closed valve. Balancing the valve element and orienting it in the system, i.e., flow-to-open or flow-to-close, also are methods to ensure proper position of the element. On the F-1 engine main valves, the balance-chamber force during mainstage will override the force of the spring in the actuator that is biased to close the valve. If control pressure is lost, the valve will remain open until pressure decays in the propellant feed system, at which time the valve will start to close. This mode allows engine shutdown by the upstream propellant prevalves if control pressure to the main valves is lost during engine mainstage.

In pilot control valves, the four-way valve provides an improvement over the use of two three-way valves to control a double-acting piston. A single four-way valve ensures control of valve position, whereas individual three-way valves may assume various positions should electrical failure occur to one and not the other. Selection of the proper actuator is influenced by the fail-safe provisions. The fail-safe mode is established early in the design to prevent having to either reselect actuators or increase spring force within an established actuator envelope. For throttling valves such as the flow-control valves on the LMDE, the fail-safe position is full open. The control circuitry and valve actuator have been designed to move the valve full open under various failure-mode conditions. Throttling valves that control mixture ratio can be programmed either to fail in a predetermined position should control be lost or to stay in the "last" position prior to the failure. Again, the proper fail-safe position for such valves is based on system analysis.

2.2.4 Actuator Type

Present operational propulsion systems utilize a variety of actuator types (table I). Details of actuator design are presented in reference 12. The actuator type best suited for mating with the valving unit depends primarily on the stroke required to achieve the specified valve operation and the force necessary to achieve the specified response. The following maximum strokes are normally associated with the actuator type listed (rotary actuators are discussed separately):

Actuator type	Maximum stroke	
	in.	mm
Torquemotor and flexure tubes	0.030	0.76
Diaphragm (metallic)	0.040	1.02
Diaphragm (nonmetallic)	0.100	2.54
Solenoid	0.125	3.18
Bellows (hydroformed)	0.750	19.05
Piston	(as limited by envelope)	

Although diaphragms of larger diameter, bellows of greater length, or solenoids with more ampere turns could increase the stroke values listed, such increases usually represent a decided disadvantage in satisfying valve envelope and weight constraints of a flightweight system. A review of table I shows, as would be indicated by the maximum stroke values, that the short-stroke feature of the poppet allows this valving unit to be mated with the widest variety of actuator types.

Ball, butterfly, blade, and sleeve valves require either that a rotary actuator be used or that the reciprocating motion of a linear actuator be converted to rotary motion by suitable linkage. The stroke required to achieve rotations up to 90° for such valves usually dictates the use of piston actuators. Notable exceptions are the butterfly prevalves on the S-II stage. These valves incorporate an eccentric linkage to achieve a 90° rotary motion with a short-stroke bellows actuator. Electrical rotary drives are employed on several valves, as indicated in Table I: notably, the F-1 engine checkout valve (ball), the J-2 engine PU valve (rotary sleeve), and the AJ10-137 engine PU valve (sliding gate or blade).

As noted, the actuation-force requirements also dictate the selection. To achieve rapid response, the actuation force required to accelerate the linkage and valve element must be imparted with a minimum actuator mass, because additional mass will require, in turn, a greater force and result in higher impact loads when the actuator reaches its stop. Following is a list of the forces or torques associated with typical actuator types on present operational hardware:

Actuator type	Force or torque to position element	
Torquemotor and flexure tube (RS-14)	30 in.-lb	3.39 N-m
Electrical motor (rotary) (J-2 PU)	100 in.-lb	11.19 N-m
Solenoid (J-2 four-way)	35 lb	0.16 kN
Diaphragm (nonmetallic) (J-2 purge control)	500 lb	2.22 kN
Diaphragm (metallic) (J-2 vent and relief)	1200 lb	5.34 kN
Piston (F-1 MFV)	6800 lb	30.25 kN
Bellows (hydroformed) (S-II prevalve)	9500 lb	42.26 kN

Greater forces or torques are possible with electrical actuation devices, but the envelope/weight penalty and increased vehicle power requirements makes direct electrical actuation unsuitable for larger valves. Electrically operated pilot valves to control actuation fluid to mechanical actuators provide a means of increasing actuation force while keeping electrical power usage to a minimum.

Timing is one of the primary considerations in selection of an actuator; it becomes vitally important when the valve is integrated into the propulsion system, particularly when the valve is part of the engine start or shutdown sequence. Repeatability in actuation time under different thermal conditions often requires utilization of thermal-compensating orifices. The actuator for the J-2 engine main oxidizer valve is an example of the use of a thermal-compensating timing orifice to control the opening time of the valve.

Leakage requirements on valves used in propulsion systems for long-duration space missions may be very stringent. Isolation valves that are explosively actuated are employed to prevent loss of pressurant. The actuators for the valves in such propulsion systems are pressurized only when the engine is firing; the pilot valves provide the seal when the system is inactive. However, considerable loss of pressurant may occur over the total accumulated engine burn time, and this loss may dictate the use of mechanical actuators such as diaphragms or bellows that exhibit zero leakage.

Selection of the mechanical actuator must consider structural limitations. In metallic diaphragms, stroke is limited, and spring rates can become excessive if an attempt is made to increase stroke. Nonmetallic diaphragms are limited by hoop stress in the convolution; the maximum hoop stress in Mylar diaphragms is 2000 psi (13.8 MN/m^2). Bellows are limited by the level of internal pressure that can be withstood. A single-acting bellows actuator with pressure applied externally as in the S-II stage prevalves represent the best structural use of the bellows. Piston actuation forces are limited only by envelope and weight restrictions.

The fluids available on the vehicle or spacecraft also influence the actuator selection. If the power for valve actuation can be derived from the propellant handled or from the inert purge or pressurant gases, a savings in net weight can be realized by the propulsion system. Hydraulic-oil control systems and associated ground support systems present the hazard of fire if a line ruptures; such failures have occurred. Pneumatic-actuated control systems are safer because the fluid in such systems usually is inert.

In propellant-actuated valves used in space vacuum, precautions must be taken in the design of the propellant vent or discharge lines. Expansion of the propellant to pressures below the triple-point pressure can result in evaporative freezing of the propellant in the vent line, thereby clogging the system and causing the valve actuator to malfunction (refs. 23 through 25). For example, a flight failure of the bipropellant valve in the Transtage engine was traced to venting of internal valve leakage through the pilot valve vent tube into the hard vacuum of space. The leaking fuel froze and blocked the valve mechanical linkage (ref. 26).

Separate hydraulic systems also are employed for engine gimbaling. However, such systems are a weight penalty on the propulsion system. A common hydraulic system for engine gimbaling and valve control (e.g., the system on the F-1 engine) offers a decided advantage in weight reduction. The use of RP-1 propellant in the F-1 engine hydraulic system further reduces weight, since no separate reservoirs are required.

Pressures employed in pneumatic or hydraulic systems for valve actuation are often dictated by considerations other than normal valve requirements. Table V lists actuation fluids and pressures for typical actuators in various operational liquid rocket engine systems.

The extremes of temperature to which actuator components will be exposed during a flight mission necessarily influences the actuator selection. The envelope restrictions require that the valve actuator be linked closely to the valve element. This integral design may mean that no effective thermal barrier can be provided. The actuators of valves handling cryogenics can therefore reach temperatures approaching that of the fluid being handled unless heaters are used (undesirable). Other thermal sources, such as the engine exhaust plume, aerodynamic heating, earth albedo, and solar radiation can alter the temperature environment. Temperature of the fluid used for actuation also is a factor. Temperature ranges of some state-of-the-art actuators employed in the Saturn V vehicle are presented in table VI.

TABLE V. – Actuation Fluids and Pressures for Typical Operational Actuators

	Actuation system		
		Pressure	
Engine system	Fluid	psi	MN/m^2
MA-5 (Atlas Sustainer)	Hydraulic oil (MIL-H-5606)	750	5.17
J-2 (S-II and S-IVB)	Helium	450	3.10
F-1 (S-IC)	RP-1 fuel (MIL-P-25576)	1500	10.34
AJ10-137	Gaseous nitrogen	145	1.00
LM Descent	Aerozine-50	230	1.59
LM Ascent	Aerozine-50	165	1.14
S-II stage prevalves	Helium	750	5.17

TABLE VI. – Operating Temperature Ranges of Some Representative Fluid-Actuated Actuators on the Saturn V Vehicle

Engine system	Valve type	Application	Actuator type	Dynamic seal	Actuator fluid	Operating temperature range F	K
F-1 (S-1C)	Poppet	Main oxidizer valve (LOX)	Piston	O-ring	RP-1	0 to +120 (RP-1 circulates in warmant passages)	256 to +322
J-2 (S-II)	Butterfly	Main fuel valve (LH_2)	Piston	Mylar lipseal	He	–250 to +140	117 to +333
J-2 (S-II)	Poppet	Fast shutdown valve (He)	Mylar diaphragm	NA**	He	–250 to +140	117 to +333
S-II stage	Butterfly	Prevalve (LOX or LH_2)	Bellows	NA	He	–300 to ambient	89 to ambient
AJ10-137	Ball*	Main bipropellant valve (N_2O_4/A-50)	Piston	O-ring	GN_2	50 (constant temperature heater blanket)	283
LMAE	Ball*	Main bipropellant valve (N_2O_4/A-50)	Piston	O-ring	A-50	+25 to 140	+269 to 333
LMDE	Ball*	Main bipropellant valve (N_2O_4/A-50)	Piston	Omniseal	A-50	+20 to 135	+267 to 331

* Quad redundant assembly

** Not applicable

Linear piston actuators employing O-rings are limited to temperatures above −65° F (219 K). Special O-rings are available for temperatures up to +500° F (533 K). O-ring-sealed actuators on valves handling cryogenics generally require some method for heating, e.g., heater blankets as used on the MOV actuator on the Atlas MA-5 engine system, or fuel recirculation through warmant passages as used in the MOV actuator on the F-1 engine. To eliminate the requirement for actuator heating, Mylar and Kel-F piston lip seals have been used effectively on J-2 engine valves, where the fluids handled are liquid oxygen and liquid hydrogen. Metallic diaphragms and bellows actuators offer the greatest operating range capability, and such actuators have been employed in valves for the Saturn vehicles.

2.2.5 Static Forces

On all valve types, maintenance of proper seal loads on poppet valves and of proper valving element position requires that force relationships among the actuator, linkage, and the valving element be known to the extent that effects of actuation-pressure tolerance, spring or bellows installed tolerance, area ratios (in pressure-balanced valves), and friction may be analyzed and accounted for in the design.

2.2.5.1 SEAL LOADS

Seal loads in poppet valves must be analyzed to ensure adequate sealing and contamination tolerance under minimum applied pressure. Combinations of minimum actuation pressure, lowest spring or bellows preload (from tolerances), temperature effects, and minimum system pressure (when a pressure-energized seal or valve balancing is employed) are investigated. Excessive seat stresses under maximum force conditions also are analyzed to ensure that poppet valve seats are not overstressed.

Design problems on seal loads that may arise are illustrated by the difficulty with the poppet main valve on the F-1 engine. In this pump-fed system, the valves were propellant-actuated and actuation forces varied from tank head pressure through pump discharge pressure. Investigation of sealing loads established that minimum sealing forces from tank head pressure were not adequate to give reliable, leak-tight shutoff. Alternate solutions were investigated, and a poppet lip seal to provide sealing under the minimum pressure conditions was considered. However, the lip seal was not deemed as reliable as the captured soft-poppet nose seal. To obtain the higher seal loads required for tight shutoff with the more reliable captured seal, a separate ground pump (GSE) was used to supply pressurized fuel to the actuator until F-1 engine start.

2.2.5.2 VALVING ELEMENT POSITION

On valves that are pressure balanced, the dynamic forces on the valving element in the open position must be resisted by combinations of actuator forces and balance-chamber forces so that valve element position is maintained without use of latches or detents. In unbalanced valves, the dynamic flow force must be resisted by the actuator forces. The requirement for holding valve position with minimum actuation pressure under maximum dynamic force conditions on the valving element may require that the actuator area be increased. In development of the valve for the J-2 engine gas generator, the need for additional actuator area created problems. Because of the sensitivity of the valve to low pressure, premature opening could be caused by internal leakage of components in the actuation system. The requirement for holding valve position under minimum actuation pressure could not be relaxed; therefore, the solution was to control leakage in the pneumatic actuation system to a level below that which would affect the gas generator valve opening.

With rotary valves such as the ball and blade, no torque is required to hold the valve in the open position, because no dynamic flow force acts to close the valve; this characteristic can be an advantage, because valving element position can be maintained without constant application of force except for spring bias. The open position of the butterfly valving element must be held against a dynamic flow force that usually is tending to close the valve coupled with the spring bias-to-close force. However, extreme disk offset can change the magnitude and direction of dynamic flow force torques (ref. 16, p. 296).

Initial flow tests on the four-way hydraulic spool valve for the F-1 engine caused the valve to cycle to the open position without energizing the start pilot solenoid valve. It was determined that the pressures on the spool overcame the spring bias-to-close force because flows on the bench were higher than those in engine operation. However, to ensure that a safe margin would exist, the spring bias-to-close force was increased so the valve would not open even with flowrates ten times those encountered during normal engine operation. Spool valve axial forces depend on the particular porting of the valve. References 27 and 28 provide methods for estimating these forces, but in practice flow tests are conducted on spool valves to ensure reliable operation free from instability.

2.2.6 Dynamic Forces

The dynamic forces acting on the valving element in the fluid stream at various stroke positions or degrees of rotation must be known, so that sufficient actuator force to move the valving element to the required position in the allotted time can be ensured. Analysis of valving element dynamic forces in pump-fed systems is particularly difficult because valve element motion occurs at a time when system pressures may be building up or decaying. Analyses of dynamic forces on a ball and a butterfly valve are given in references 29 and 30, respectively.

From the engine-sequence tolerances, the maximum and minimum pressures for various valve-element positions can be established by superimposing the curves for valve-element position versus time and pump discharge pressure versus time. In pressure-fed systems, the pressures upstream of the main propellant valve vary within a band determined by the tolerance on the tank-pressurization regulator.

2.2.6.1 VALVE OPENING

Actuator force required to open the valve must be established accurately. Although analytical techniques such as flow-net methods (ref. 31) have been used in attempts to predict the dynamic forces on the valve element, experimental flow data on the valve are required to verify calculations. The valve opening problem discussed in section 2.2.7.6 is an example of a condition in which the actuator force margin was not sufficient to open the valve against increasing pump discharge pressure. As a result, the butterfly disk stalled in a partially open position, and the engine malfunctioned.

2.2.6.2 VALVE CLOSING

Actuator force required to close the valve must be verified by test. With propellant-actuated valves, accurate estimates of closing force requirements are necessary, since decaying pump discharge pressure will reduce any safety margin if closing is delayed. On the H-1 engine, a decay in closing of the butterfly main fuel valve resulted in unreliable shutoff because the actuator force was not sufficient to overcome resistive friction forces in the final few degrees of travel as the butterfly disk engaged the lip seal. Reliable shutoff was achieved by increasing the closing-side piston area on the valve actuator. Difficulty in providing sufficient closing force on a butterfly valve after the lip seal is engaged is accentuated in designs in which Belleville springs are used to "kick" the disk out of the seal on opening. When the valve closes, these springs must be compressed.

In the case of the fuel-actuated poppet-type main fuel valve on the F-1 engine, a delay in closing occurred occasionally during engine tests. Surfaces on the balance piston in the valve were forming a metal-to-metal seal that reduced the net closing force. The mating surfaces were machined to prevent any possibility of such a seal developing and changing the force balance in the valve.

2.2.7 Valve Response

Valve response time is defined as the total time elapsed from receipt of signal until the valve reaches the full-open or full-closed position. The signal may be electrical, a pressure change from a sequence valve in a pressure-ladder sequence, or simply a rise or decay in system pressure from some established datum. Within this total period of valve response time, there can be electrical delay time and pneumatic or hydraulic delay time that elapses between receipt of signal and valve first motion. That portion of valve response time between valve first motion and full-open or full-closed position is termed valve travel time. The following factors affect valve travel time:

- Dynamic forces acting on the valving element and balancing chambers
- Friction forces opposing valve opening or closing motion (from bearings, shaft seals, and lip seals)
- Displacement of fluid from balance chambers
- Inertia of moving parts
- Length of stroke required to operate the valving element
- Force available from the actuator (force-vs-time relation due to pressurizing or venting characteristics of the actuator)
- Spring rates of installed springs and bellows

2.2.7.1 ELECTRICALLY OPERATED VALVES

Small poppet valves used in pilot control applications, RCS thruster main valves, and low-capacity system vents are actuated directly by solenoids or dc torquemotors. In such short-stroke valves, the electrical delay represents the most significant portion of the total valve response time. The valve travel time from first motion to full open comprises only a small percentage of the total response time. To achieve fast response and low steady-state current drain, special driving circuits are used to shape the peak driving voltage during actuation; reference 12 describes these special driving circuits. In many applications, a simple driving circuit consisting of a power supply and mechanically operated switch is sufficient. Typical response characteristics for these types of valves are shown in Table VII.

The dc torquemotor has characteristically shorter electrical delay times than a solenoid of comparable size and provides a means of reducing total valve response time.

2.2.7.2 PNEUMATICALLY AND HYDRAULICALLY OPERATED VALVES

On electrically piloted, pneumatically operated valves or valves controlled by sequence valves in a pressure-ladder-sequence engine control system, the factors that affect response

TABLE VII. – Delay and Travel Times in Representative Electrically Actuated Valves

Engine	Valve application	Actuator type	Valve stroke in.	Valve stroke mm	Nominal electrical delay, msec	Nominal valve travel time, msec	Nominal response time, msec
J-2	Four-way pneumatic control	Plunger solenoid	0.028	0.711	18.5	3.7	22.2
SE-8	Propellant	Plunger solenoid	0.016	0.406	3.2 (auto coils)	1.0	4.2
					6.5 (manual coils)	1.0	7.5
J-2	Emergency vent	Flat-face-armature solenoid	0.016	0.406	7.0	1.5	8.5
RS-14	Bipropellant	dc torquemotor	0.030	0.762	37.0*	3.0	40.0
					7.0**	3.0	10.0

* Pressurized

** Unpressurized

time are flow capacity of the control valving, line sizes, initial total volume, and actuator swept volume. In addition, if the actuator uses propellant as the actuation fluid, the engine sequence on pump-fed systems may affect valve response, or valve opening transients in pressure-fed engines can seriously affect available actuation pressure and thereby alter valve response. For example, erratic opening of the bipropellant valves on the AJ10-137 engine was traced to changes in the valve actuation supply pressure caused by pressure transients during opening of the redundant ball valves. The propellant was replaced with gaseous nitrogen for the actuation fluid.

In pump-fed systems, curves showing discharge-pressure buildup or decay must be developed and used to determine the actuation force at any time. On the F-1 engine, for example, slow closing times of the poppet main fuel valve were noted during engine static tests. On review of engine sequences, it was determined that the main fuel valve was programmed to close later in the shutdown sequence than was specified by the valve design requirements. As a result, pumpout pressure was lower, and closing force from the actuator was decreased to such an extent that valve closing time was affected. Programming the valve as specified corrected the problem.

Maximum specified response times are important in pump-fed systems. During the start sequence, if valve opening is delayed or a slower opening time is required, the valve must be opened against a higher dynamic force on the valve element. Delayed closing times on butterfly valves used as thrust-chamber main propellant valves can present a problem in propellant-actuated systems, as described earlier for the H-1 and F-1 engine main valves (sec. 2.2.6.2).

2.2.7.3 FRICTION

Friction has caused slow response or unreliable operation of valves. Sliding friction in solenoid valves has resulted in sticking or slow response. Plunger-type solenoids in many of these valves are subject to jamming by contamination. The flexure-mounted poppet and flat-face armature are used to avoid plunger friction. The flexure-tube poppet valve actuated by a dc torquemotor is another design used to avoid friction. In large poppet valves, galling of guides and resulting friction may also affect valve response.

The early version of the oxidizer turbine bypass valve on the J-2 engine was designed with a single-acting pneumatic actuator and utilized a spring to close. Because of body distortions from the severe thermal environment, friction in the bearings and between the disk and the housing became excessive and caused the valve to "hang up" when closing. Critical clearances were increased, and in the final production-configuration valve a double-acting actuator provided increased closing force.

Valve body distortions from dynamic loads and cryogenic cycles caused unpredictable friction in the butterfly prevalves on the S-II stage during the development program. The problem was corrected by stabilizing the housing during the machining process.

2.2.7.4 INERTIA OF MOVING PARTS

In rapid-response valves, the actuator, linkage, shafting, and valving element must be accelerated to high velocities. These masses in motion then must be brought to a stop when the valve reaches full-open or full-closed position. Energy-absorbing techniques are used to stop the masses without damaging either the parts in motion or the stationary portions of the valve such as the seat.

The actuator mass in poppet valves can be decoupled from the moving poppet and shaft by the use of a "T"-slot coupling, as shown in figure 7. This technique is applicable to both small solenoid valves and poppets with hydraulic or pneumatic actuators. In the F-1 engine poppet valves, a hydraulic dashpot in the actuator shaft (fig. 8) is used to slow the valve at the end of its closing stroke; no decoupling is necessary in this balanced poppet design, because actuator mass is small in comparison to the poppet. In both hydraulic- and pneumatic-actuated valves, the impact has been cushioned by restricting flow from the vent side of the actuator. In butterfly and ball shutoff valves, the actuator usually is decoupled from the linkage, crank, shaft, and disk by allowing the actuator piston to strike the end of the cylinder. Valve-response calculations must consider impact forces. The analysis (ref. 32) includes a determination of minimum valve travel time based on the stresses in the shaft and linkage that result from retarding or stopping the rotating disk. Valves have been damaged during checkouts by operating them inadvertently at a rate faster than the design rate, the result being failure of linkage and shafts.

In ball valves, the mass of the ball and the high seal loads can make it difficult to achieve rapid response. When the actuator piston stops by striking the end of the cylinder, the actuator mass is decoupled; however, the large moment of inertia of the ball results in critical problems with the drive shaft, because ball rotation must be retarded and stopped by the shaft without the shaft yielding.

A hollow ball design (fig. 9), used on the gas generator valve on the F-1 engine, is one solution for reducing inertia forces in fast-response ball valves. A hollow drive shaft can also be employed; this kind of shaft not only reduces the inertia forces, but allows the energy to be absorbed more uniformly along the length of the shaft without being concentrated at the smallest shaft section. The LMDE bipropellant shutoff valve utilizes hollowed-out and truncated ball valving elements to reduce inertia.

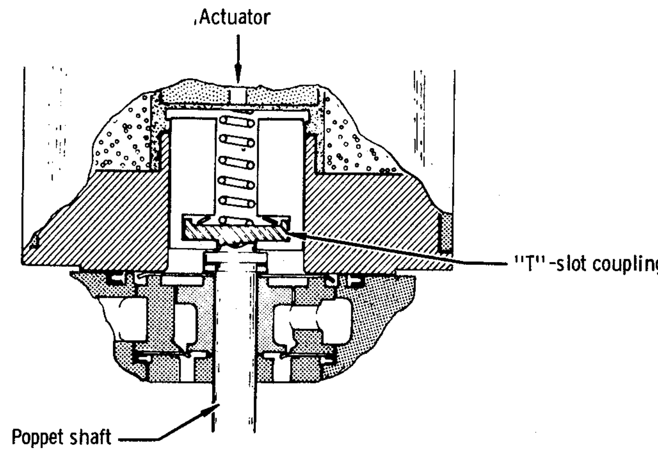


Figure 7. - Cross-section drawing of poppet valve with mechanism to decouple poppet from actuator.

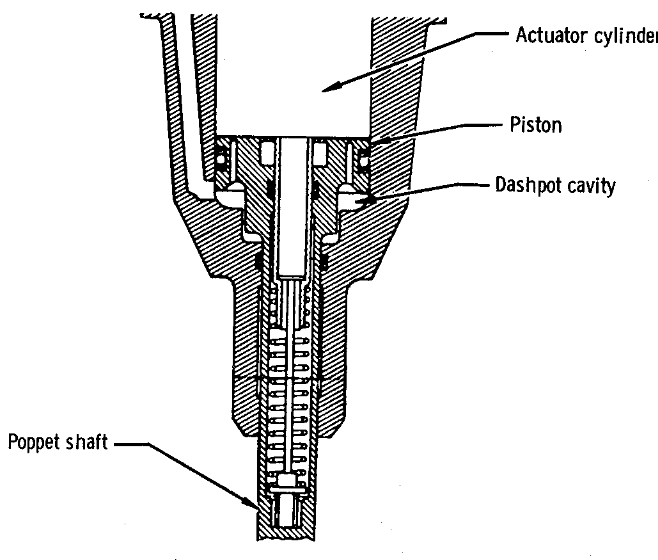


Figure 8. - Cross-section drawing of poppet valve with dashpot to cushion closing.

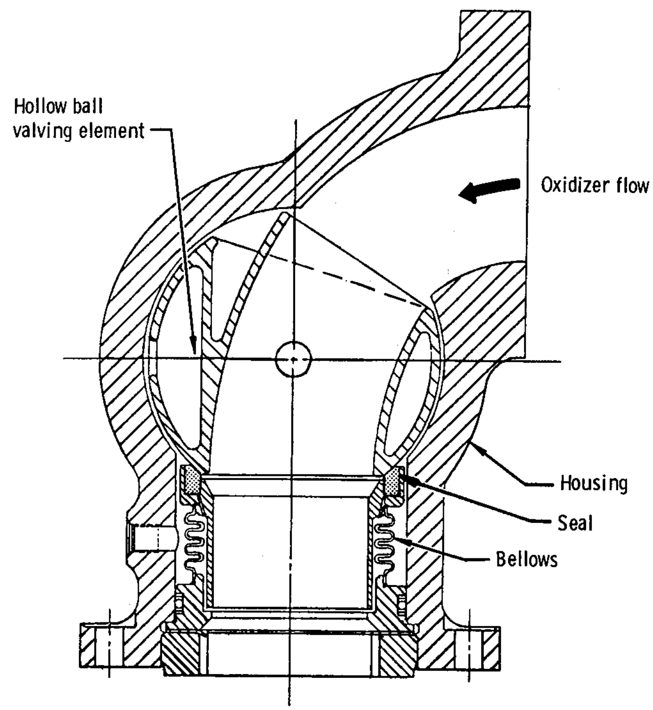


Figure 9. - Cross-section drawing of hollow-ball valving element in bipropellant valve on gas generator on F-1 engine.

2.2.7.5 LENGTH OF STROKE

The short-stroke feature of the poppet provides a distinct advantage over other valve types in achieving rapid response. The poppet diameter can be increased to reduce the stroke required to achieve full flow. Blade valves offer a similar advantage because the degree of rotation required for full flow is less than that for butterfly or ball valve elements, which usually require a 90° rotation of the element to achieve full-open position.

Actuator linear travel also is dependent on the design of the mechanism used to translate the linear motion to rotary motion. By use of either the eccentric design described in section 2.3.1 or a small-diameter pinion and mating rack, the actuator stroke to achieve 90° rotation can be reduced. The small moment arm will require a higher actuator force and result in a choice of either a larger piston area or higher actuation pressures for short-stroke actuators.

2.2.7.6 TIMING REPEATABILITY

Valve operation must be repeatable if the valve is to provide the required propulsion system control functions. An acceptable tolerance is determined first from engine analysis and later from engine development testing; failure of the valve to operate within this tolerance time span can seriously affect engine performance. The valve response time previously discussed is normally specified to be within a range of time that is required by the engine system; the actual opening and closing times of the valve when installed and functioning must lie within this required response envelope. Timing is usually achieved by providing suitable orifices in the pneumatic or hydraulic actuator to alter the force-versus-time relationship of the actuator and provide the required opening or closing time.

Once the desired valve timing is obtained, the effect of thermal changes in the actuator and changes in actuation fluid temperature must be compensated for to achieve the desired repeatability. Friction forces during actuation vary from valve to valve and in a particular valve because changes in temperature of the components alter clearances. These variable forces therefore must be kept small in comparison to other forces if repeatable timing is to be achieved. Ideally, friction forces should not exceed 10 percent of the total resistive force the actuator must overcome. To ensure that adequate force margin exists and that timing is not affected by changes in friction forces, opening or closing actuator forces usually exceed the total resistive forces by a factor of at least 1.5.

Lack of repeatable operation of the butterfly main oxidizer valve on the J-2 engine posed early development problems. It was required that the valve move from the first-stage 14°-open position to full-open position in approximately 2 seconds. A delay in valve first motion because of restricted venting due to chilling caused the valve to stall in the 30°-open position, and the engine malfunctioned. The stall was the result of rapidly increasing pump outlet pressure that required the valve to open against a higher hydraulic torque. The solution was the design of a thermal-compensating orifice that maintained a constant effective flow area and thereby prevented the decreased differential pressure across the actuator piston caused by the restricted venting. Heater jackets to counteract the chilling were considered but were rejected because of the power requirements.

When two valving elements are in series or in series-parallel redundant arrangement, repeatable valve timing can be difficult to achieve. The problem has been simplified by allowing one set of valve elements to move more slowly than the other set. On the AJ10-137 engine, for example, the fast set of valve elements moves in 400 to 600 msec, and the slow set, in 625 to 850 msec; the slower set controls the flow of propellants to the engine.

Valve timing on bipropellant valves is important in that it ensures a lead of one propellant into the combustion chamber. On the bipropellant poppet valves for the H-1 and J-2 gas generators, a yoke with an adjustable gap is attached to the actuator on the fuel poppet; the yoke contacts the oxidizer poppet shaft after the fuel poppet has already opened. On rotary valves, opening time can be regulated by adjusting linkage or ball rotation of the fuel ball relative to the oxidizer ball. In blade valves using a common actuator, propellant lead adjustment is provided by rotation of one blade relative to the other.

2.3 DESIGN INTEGRATION OF VALVE SUBASSEMBLIES

The complete design of basic valving unit and actuator combination requires selection of a power transmission device and subsequent integration of the device with the valving element and actuator in the valve housing. The interactions of thermally induced loads, pressure-induced loads, and loads imposed on the valve structure externally through the interface mounting points are established, and positive design steps are taken to prevent such loads from interfering with valve operation. The environment of the valve assembly during the mission duty cycle of the propulsion system is considered, and appropriate measures to account for environmental effects are taken. Provisions for filtering, purging, flushing and draining are made. Instrumentation is provided both during the development phases of the valve and as part of the flight instrumentation. During static testing of the vehicle's propulsion system, valve latching provisions may be required. To ensure that the various valve subassemblies can be assembled, the designs are thoroughly checked and tolerance stackups accomplished. "Goof-proofing" features that minimize the chances of improper assembly are incorporated in the valve subassemblies.

2.3.1 Integration of Actuator and Valve

Physical integration of the actuator and the valve to form an assembly of minimum envelope and weight is a prime factor in the design of aerospace valves. A compact valve package is desirable also from a vibration standpoint, because projection of the actuator from the valve body will make necessary the use of struts and webbing to ensure structural integrity under the random and cyclic vibrations that exist in the engine environment.

Close mating of the actuator with the valve requires consideration of the temperature extremes that occur in valves in cryogenic service. In addition, positive separation of propellant and actuation fluid must be provided when incompatibility could lead to a reaction within the valve if propellant leaked past internal seals. Vented or purged cavities are utilized to separate leakages of incompatible fluids (e.g., leakages that may occur in bipropellant valves with common shafts or with oxidizer valves having hydraulic actuators). Figure 10 shows the design used for the F-1 engine main oxidizer valve to prevent the actuator fluid (RP-1) and the propellant (liquid oxygen) from contacting. For bipropellant valves such as those on the Transtage AJ10-138 engine, the propellant leakage past the seals of the common actuator shaft is separated by a vented cavity as shown in figure 11. Because the actuator is operated by fuel and is located on the fuel side, actuator leakage is not critical from a contamination standpoint.

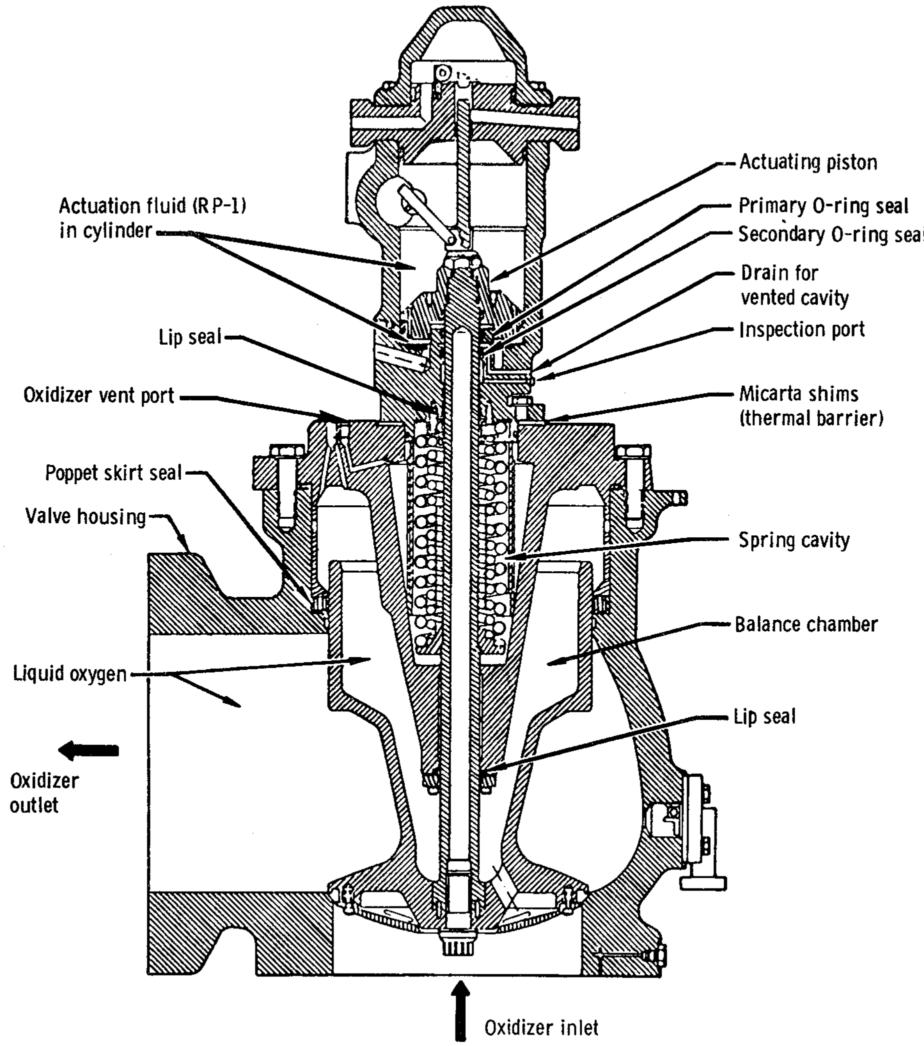


Figure 10. - Cross-section drawing of poppet main oxidizer valve on F-1 engine showing separation of liquid oxygen and RP-1.

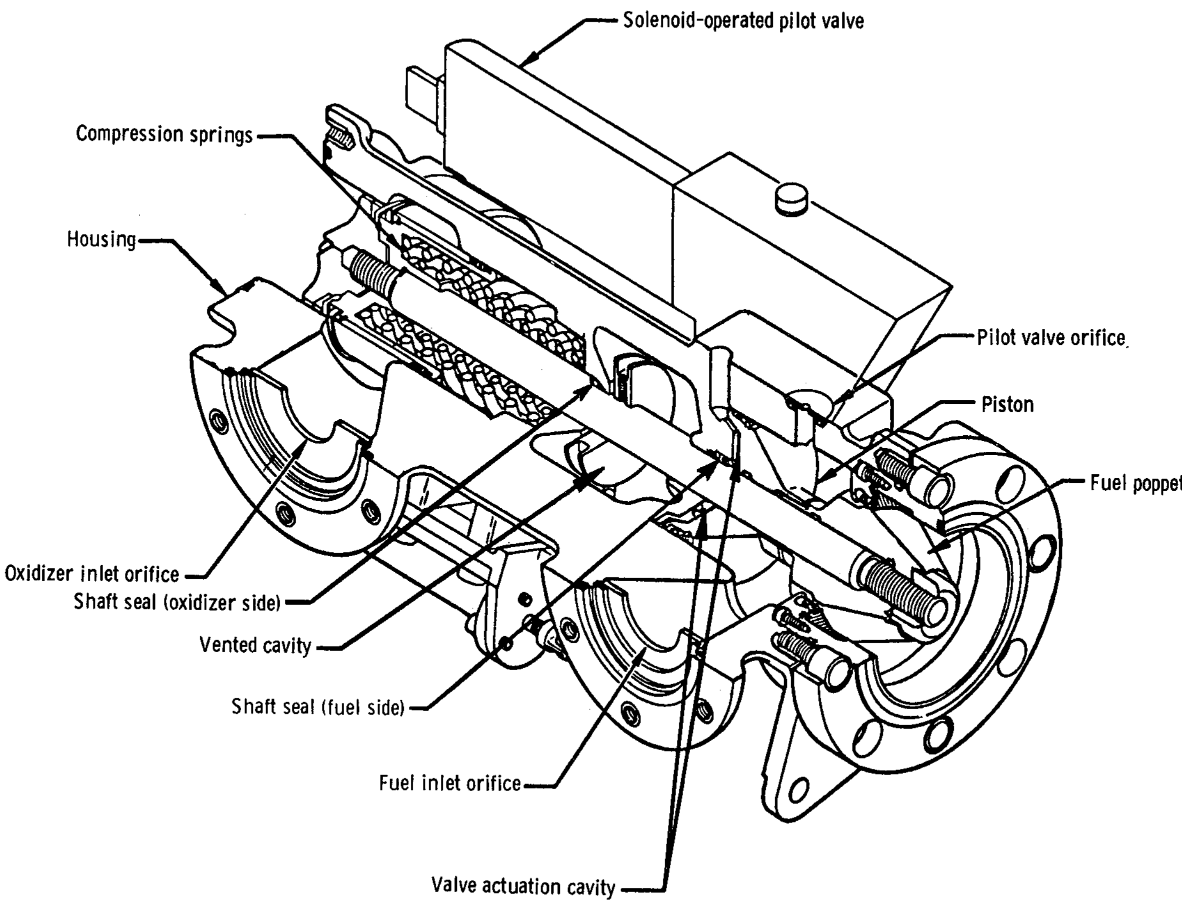


Figure 11. - Isometric cross section of bipropellant valve on AJ 10-138 engine showing vented cavity to separate oxidizer (N_2O_4) and fuel (A-50).

In electrically actuated valves, two design approaches, termed "wet operation" and "dry operation", are used. In wet operation, the propellant or fluid being controlled is allowed to contact the armature material; in dry operation, the fluid is isolated from the armature. In plunger-type solenoid actuators on the SE-8 RCS propellant valves, wet operation is utilized. In these valves, the plunger, with an integral Stellite ball, reciprocates within the armature. Clearances between the plunger and the armature bore are critical because close tolerance must be maintained for alignment of the poppet. Armature material must be both compatible with the propellant and possess good magnetic properties, i.e., high permeability. Although close coupling of the valve element and actuator is possible in wet-operation designs, plunger-type solenoids have been subject to sticking caused by contamination in the close sliding fits of the armature bore.

Sliding fits that are subject to contamination jamming in small electrically actuated poppet valves are eliminated by the use of flat-face armatures or dc torquemotors with flexure tubes. In the case of the flat-face armature, wet operation is used, the service fluid or propellant contacting the armature face; the poppet is flexure mounted. The flexure-mounted poppet and flat-face armature design shown in figure 12 is used for an emergency vent on the J-2 engine.

Although the flat-face-armature solenoid will have a greater internal volume upstream of the seat than a plunger solenoid and therefore a slight weight penalty, both the flat-face-armature and plunger-type solenoids can be designed to minimize downstream system volume between the seat and injector. This downstream volume, termed "dribble" volume, is especially important in RCS propellant valves, where repeatable generation of small impulse bits is important; in these valves, system volume is kept to a minimum. One disadvantage of the flexure-mounted poppet and flat-face armature designs for RCS propellant valves is that the internal volume is larger than that of plunger solenoids.

Torquemotor actuators are operated dry, and flexure tubes link the actuator with the poppet. An example of dry operation involving flexure tubes to actuate the poppets is the small bipropellant valve on the RS-14 engine. Dry operation can also be achieved by use of bellows or diaphragms to separate the propellant or fluid being controlled from the armature material. Volumes in this kind of valve are small.

Actuators for cryogenic valves usually are located out of the fluid stream so that temperature cycles are less extreme. The need for creating a thermal barrier on a cryogenic valve incorporating a hydraulic actuator usually dictates a separate housing. In the butterfly valve designs for the Atlas, Thor, and H-1 engine main valves, the actuators are separate and are bolted to the valve housing. In these valves, the actuators have O-ring piston seals, and heater blankets are required to maintain proper operating temperatures. Because a thermal barrier reduces heater-blanket power requirements, the two-piece assembly uses an asbestos gasket between the actuator and the valve housing.

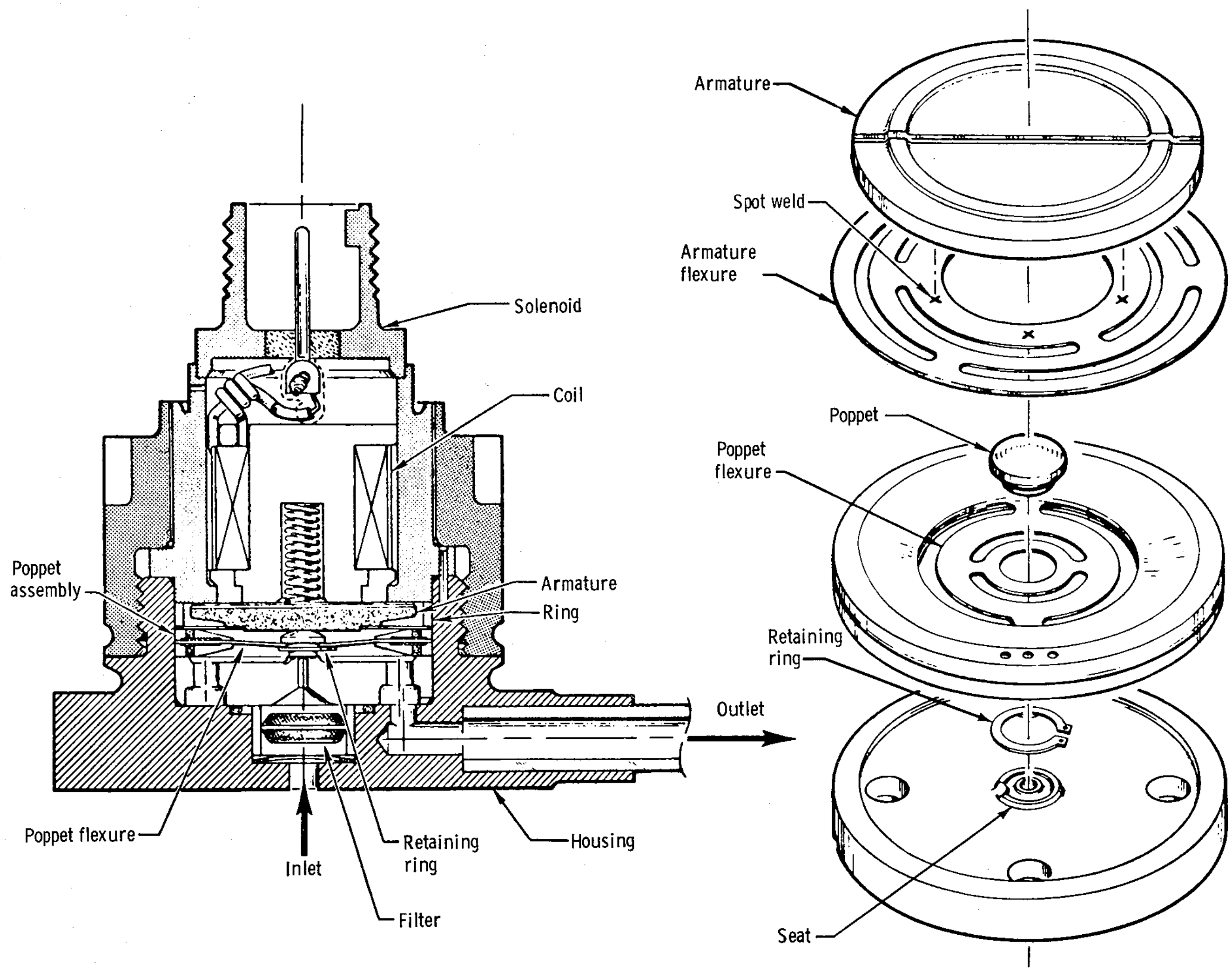


Figure 12. - Cross-section drawing of solenoid valve with flexure-mounted flat-face armature and poppet (exploded view of flexure details).

Integral valve-and-actuator housings have been utilized in the thrust-chamber main valves for the J-2 engine. The advantages of the common housing are reduced weight, reduced external leak potential, improved linkage and piston alignment, and ease of assembly. In an integral design, the seals must be capable of operating at cryogenic temperatures, since the thermal barrier that existed in the two-piece design is eliminated. Mylar lip seals were developed for the actuators on the butterfly main fuel and oxidizer valves on the J-2 engine to provide a pressure-energized, low-temperature seal.

Problems developed when the integral valve-and-actuator housing was used in larger valves. On the S-II stage butterfly prevalve, valve body distortions in the one-piece housing design caused seizure when actuation was attempted after the housing had been exposed to thermal cycles. Cryogenic stabilization of the valve body during machining eliminated the later distortion.

Blade valving elements used on the Atlas and Thor engines are integral with the gas generator dome casting and are driven by splined shafts from a common actuator mounted to the dome assembly. Such valves must withstand not only cryogenic temperatures, but also heat soakback from the combustor.

2.3.2 Transmission Devices

Mechanical devices for transmitting or converting actuator motion to the motion required to position a valving element can take one of several forms: shafts to transmit linear motion to a poppet valve; cranks, racks and pinions, and eccentrics to convert linear motion to rotary motion for positioning ball, butterfly, sleeve, and blade valving elements; and rotary shafts to transmit rotary motion directly to the valving element. Various types of mechanical linkages for converting linear motion to rotary motion are illustrated in figure 13.

The crank-and-link design (fig. 13(a)) is widely used for power transmission in ball and butterfly valves; swivel bearings in the linkage reduce problems caused by misalignment. The slotted crank (fig. 13(b)) is utilized on the ball valves for the LMAE; the slotted crank is a more compact linkage than the clevis and pin, but is limited to lower actuator forces because of high friction loads on the pin moving in the slot.

Rack-and-pinion linkages (fig. 13(c)) have been successfully used as transmission devices on ball and butterfly valves. The design offers a more compact envelope than the crank and link, but production costs are higher because of the gear cutting; gear profiling tolerances must be closely held to minimize backlash. Conventional gear materials such as 9310 steel have been used; however, corrosion in the valves led to gear-tooth failure.

Eccentric devices (fig. 13(d)) offer large rotational movement for relatively short linear strokes; however, the short moment arm increases bearing loads. The high loads usually

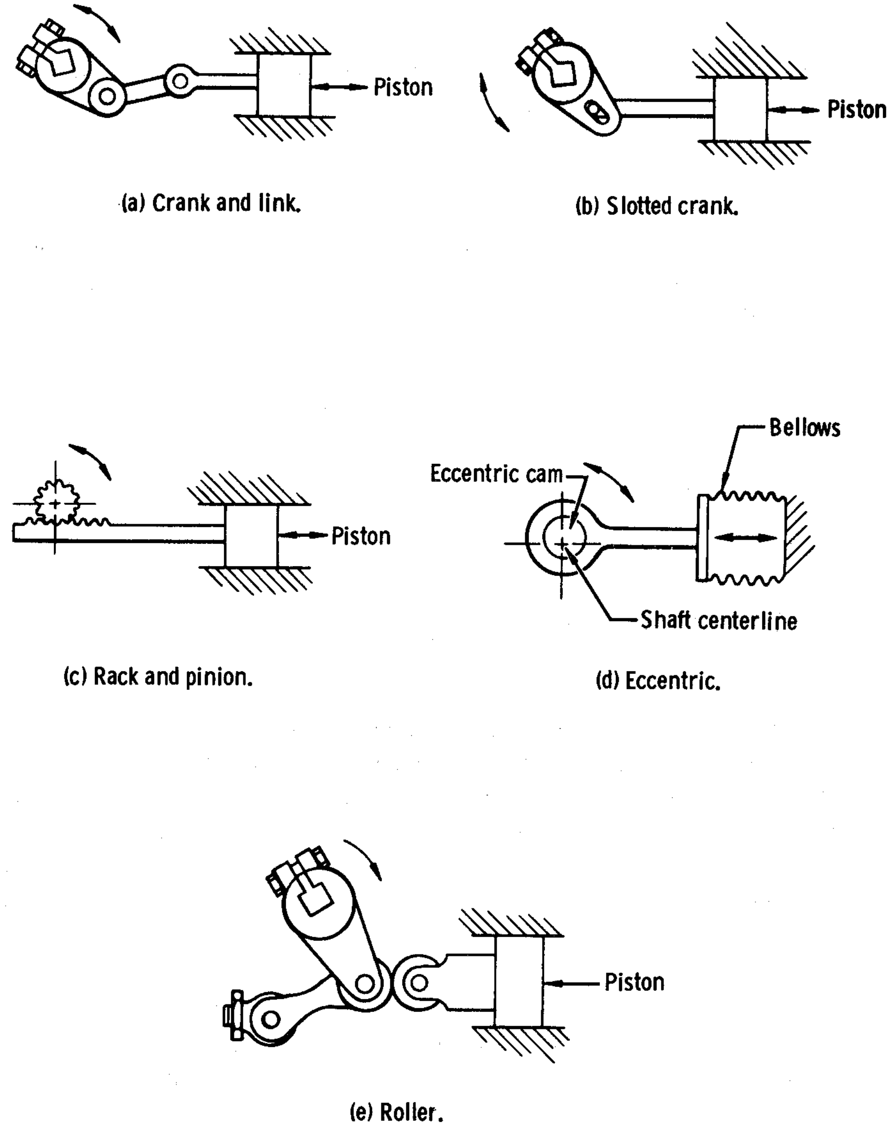


Figure 13. - Sketches of mechanical linkages for converting actuator motion from linear to rotary.

require the use of rolling-contact bearings. The eccentric has excellent characteristics for minimizing backlash. The short stroke enables bellows to be utilized. The prevalves on the Saturn S-II stage are operated by a welded-bellows actuator with motion translated by an eccentric.

Rollers (fig. 13(e)) have been employed to rotate butterfly valve disks. Although the design shown operates in only one direction, tandem rollers with a double actuator can be utilized. Rolling-contact bearings are used in the roller because of the high side loads. The design has been employed successfully on the J-2 engine MOV for first-stage positioning of the butterfly disk during the engine start sequence.

Linkage misalignment during assembly has created problems. If a separate crank and drive shaft are employed, a linkage adjustment may be required to align the linkage and position the disk properly. An error in adjustment may result in galling and damage to the valve when it is actuated. An integral drive shaft and crank not only eliminate linkage adjustments and improve alignment, but also reduce weight and simplify assembly. The integral shaft is applicable to both the crank and link and the slotted crank.

Thermal contraction or expansion can cause linkage misalignment that can be especially severe in large cryogenic valves with aluminum bodies and CRES shafts. Misalignment can cause galling, and valve timing can be affected. Spherical bearings have been utilized in the linkage of such valves to reduce alignment problems.

A number of alternate methods are used to retain pins and linkages, with snap rings finding wide application. Cotter pins have been utilized; however, broken pins have resulted from vibration. Threaded retainers can loosen when used on rotating parts and are avoided. If space is limited and the installation is "blind", use of a snap ring can result in misinstallation and possible loss of the ring.

2.3.3 Transmission Shafts and Bearings

The transmission of actuator motion to the valving elements of butterfly, ball, and blade valves requires that the rotary shaft be supported on bearings that will withstand the radial and axial loads encountered; the bearings are sealed by appropriate dynamic or static seals. If axial thrust loads can be reduced or absorbed by separate thrust bearings, journal or needle bearings usually are selected in preference to ball bearings, because larger housing bores are required to accommodate the outer race of the ball bearings.

The valving elements of butterfly and ball valves can be designed to pick up the axial loads by use of cross pins in the case of butterfly valves with separate idler and drive shafts (fig. 14) and by use of integral double shafts in the case of ball valving elements (fig. 15). In these designs, the small axial loads result from seal loads only. If such shaft force balancing

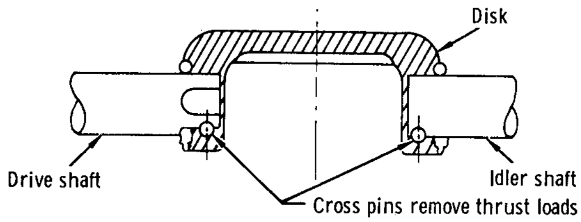


Figure 14. - Cross-section sketch of butterfly disk shaft with cross pins.

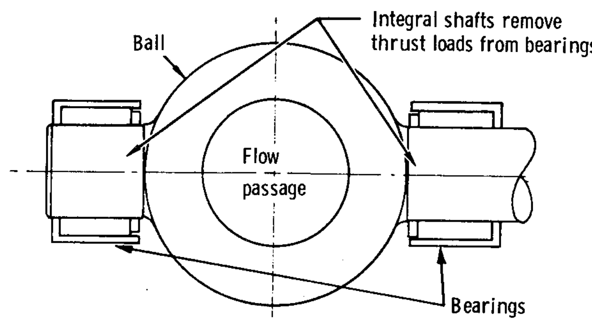


Figure 15. - Sketch of ball valving element with integral double shaft.

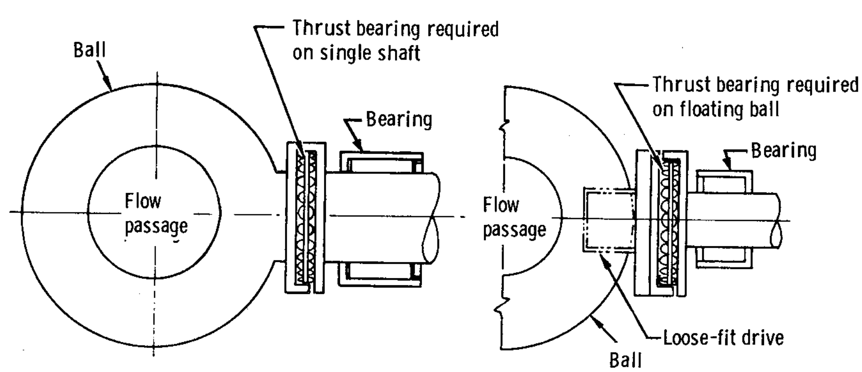


Figure 16. - Sketches of ball valving element with integral single shaft and with floating-ball shaft.

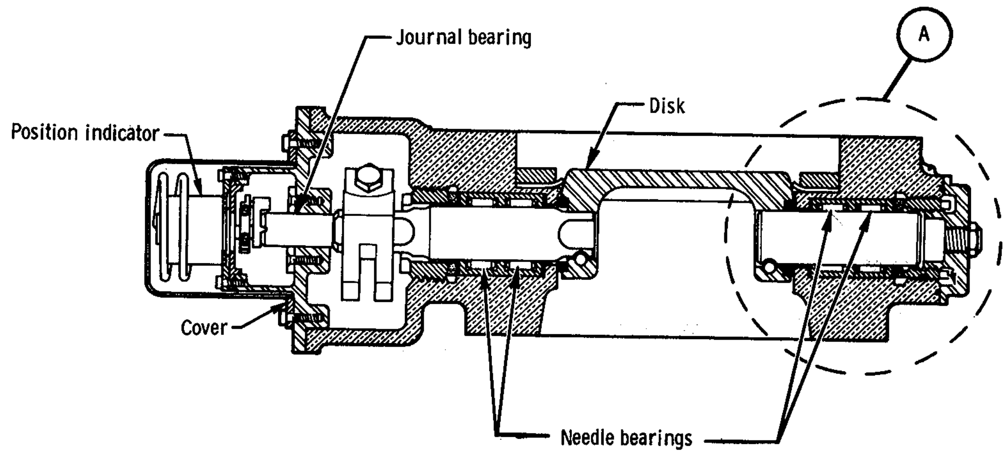
is not employed, then thrust bearings are required, as in the case of the ball valve with only a single integral shaft or with a floating shaft (fig. 16).

Ball bearings can provide rolling elements with sufficient rated capacity for both the radial and axial loads and are used when thrust forces are small. The journal bearing provides a simple method of supporting the shafting; however, because of friction, the design is limited to relatively low loads. Dry-film lubricants can be applied to increase the load-carrying ability. Journal bearings are used primarily in conjunction with rolling-element bearings as the outer bearing on drive shafts on ball and butterfly valves. Self-aligning journal bearings have also been utilized; however, the self-aligning bearing can present difficult sealing problems. Design details for bearings in valves are presented in reference 2.

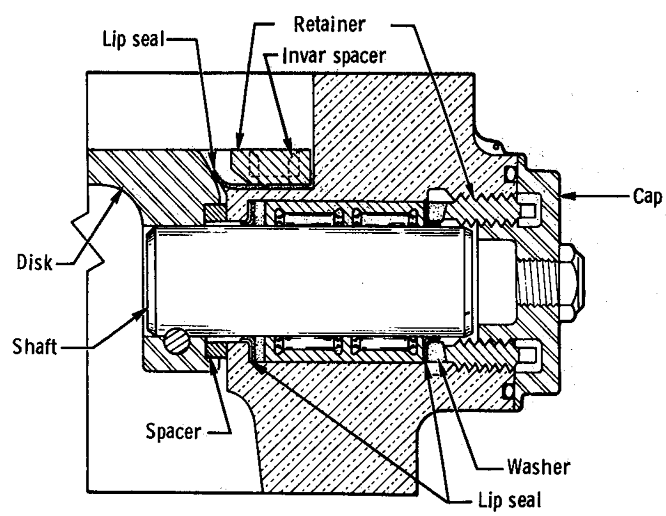
To prevent exposure of the bearing surfaces to the service fluid, seals usually isolate the bearing from the fluid in the flow passage. In thrust-chamber main valves, the moisture from the atmosphere can enter through the injector of the engine to reach bearings that are not sealed from the flow system. Bearing materials that are widely used in cryogenic valves often are susceptible to corrosion from moisture (e.g., 440 C). With such materials, good seals are required to isolate the linkage, shaft, and bearing cavity from the atmosphere to prevent corrosion of parts. Vent port check valves are used to vent these cavities and still provide a barrier to the entry of moisture.

Even though seals on the shaft isolate the bearings from the service fluid, corrosion can still occur (e.g., from leakage of storable propellants such as nitrogen tetroxide and chlorine trifluoride). Materials for bearings, races, and bearing retainers must be selected accordingly. Highly stressed parts (e.g., retainers that develop high hoop stresses from press-fit bearings) must be fabricated of material not subject to stress corrosion. On the early LMAE valves, 2024-T4 aluminum, which is highly susceptible to stress corrosion, was used for the bearing retainer for the needle bearing outer race. Leakage of the corrosive oxidizer resulted in cracking of the retainer. The solution was to change bearing retainer material to 6061-T6 aluminum.

To reduce the weight and size of the bearing assembly, rotating shafts for ball and butterfly valves often are designed so that they serve as the inner race for the rolling elements. With storable propellants, use of the shaft as the inner race presents no special problems. In cryogenic service, however, use of a heat-treated hardened shaft as the inner race has resulted in instances of brittle fracture of the shaft when the valve was actuated at cryogenic temperature. Reducing the hardness of the shaft makes it more ductile; however, it is also more susceptible to surface indentation and ultimate bearing failure. Although bearing assemblies using the shaft as the inner race have been used successfully, several shaft failures occurred when valves operated too rapidly as a result of a malfunction. A separate inner race on a shaft that has good ductility at cryogenic temperature proved satisfactory. Some successful valve designs have avoided the use of dynamic shaft seals and have allowed the service fluid to reach the actuator and linkage cavity. The bearing surfaces for such valves



(a) Cross-section drawing of valve.



(b) Cross-section drawing of bearing details in (A)

Figure 17. - Typical design, with bearing details, for butterfly main oxidizer valve.

must exhibit good corrosion resistance, because the bearings are exposed to more severe conditions than are bearings in designs incorporating shaft seals. One successful design used in the S-II stage butterfly prevalve utilizes an Inconel 718 shaft with beryllium-copper journal bearings.

Figure 17 shows a typical design for a butterfly main oxidizer valve in which shaft lip seals are used to seal the bearing cavity from the service fluid. The seal loads are absorbed by the outer race retainer. The outer bearing of the drive shaft is a journal bearing. Although the aluminum housing cover is used as the bearing material in the valve shown in figure 17, separate bearing inserts have been found more satisfactory. The inner drive shaft bearing and the idler shaft use needle rolling elements.

Figure 18 shows a typical redundant bipropellant ball valve assembly in which a common actuator shaft engages two drive shafts. The actuator crank and shaft are supported by needle bearings, and the drive shafts are journal bearings that use the valve body material for the bearing.

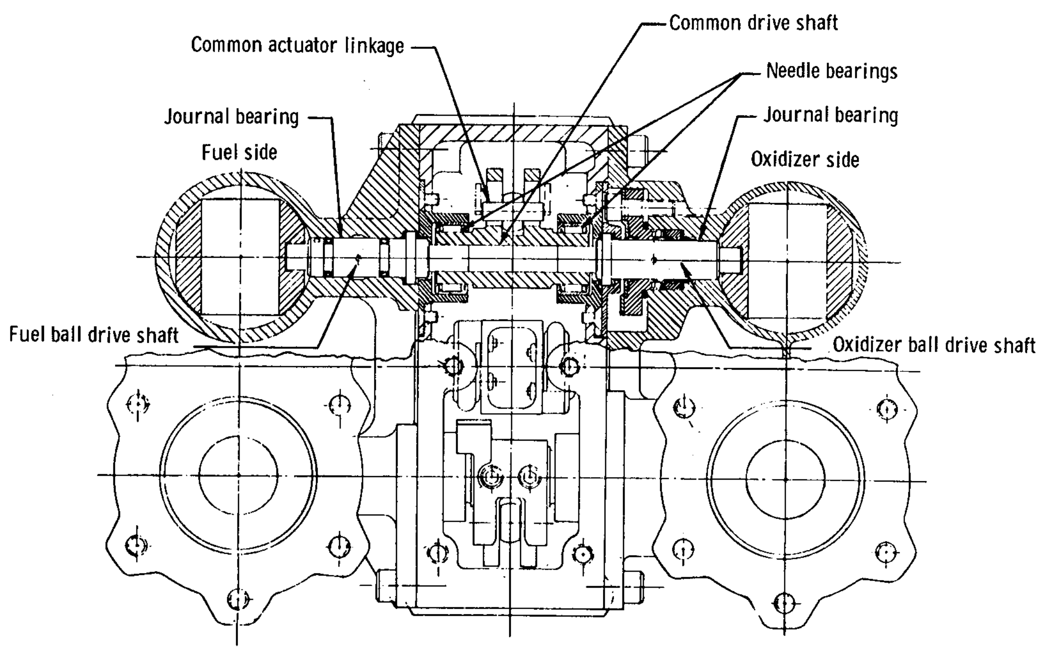


Figure 18. - Cutaway view of redundant bipropellant ball valve assembly (LMAE).

2.3.4 Thermal Expansion/Contraction, Distortion, and Loads

The valve assembly design must include provisions for changes in loading of sealing surfaces and clearances in bearings resulting from thermal expansion or contraction of materials. The valve may be subject to thermal transients from rapid chilling (room temperature to −423° F [21 K]) in cryogenic systems or rapid heating (room temperature to 1400° F [1033 K]) in hot-gas systems. Such transient conditions can pose severe design problems, and often only repeated testing of the assembly can provide sufficient data to the designer to alleviate the condition and ensure reliable operation. After the temperature of the components of the assembly has stabilized at steady-state conditions, dimensional changes are calculable, and provisions to compensate for the thermal changes can be included in the design.

Permanent distortion may occur in components of the assembly because of thermal cycling. Such permanent changes are minimized by proper selection of materials and use of stabilization techniques during fabrication of the parts.

Thrust-chamber main valves usually are chilled adequately prior to valve operation by the opening of prevalves early in the countdown to allow cryogenic fuel or oxidizer to condition the valves. Separate chilldown flow systems to recirculate propellants also are provided for engine conditioning. When upstream ducting is oriented so that a gas pocket forms, complete chilldown is prevented. In instances where chilldown was not completed, thermal shock resulted in cracked valve housings. Thin sections in a housing are especially prone to thermal shock failure, since they chill more rapidly than surrounding heavier housing sections and the thermally induced stresses soon exceed the ultimate strength.

During chilldown of a valve, anomalies may occur as a result of nonuniform dimensional changes. For example, in development of a butterfly valve, an aluminum butterfly disk was used together with an aluminum body. The disk chilled much more rapidly than the surrounding aluminum body that held the lip seal; the result was loss of diametral interference between the lip seal and the disk. Leakage occurred until the temperature of these valve assembly components stabilized. Use of a stainless steel butterfly disk solved the problem.

The position of the butterfly valving element during chilldown can influence leakage characteristics and lip seal life. If a valve is chilled with the disk in the open position, the lip seal will be unsupported, and its final chilled shape may result in too much diametral interference and cause failure. If the valve can be chilled in the closed position, the lip seal support during chilling will help control the final chilled shape.

Ball valves exhibit good chilldown characteristics in either the closed or open position, because the seals are in continuous contact on the ball and are preloaded by mechanisms that provide sufficient force to compensate for any thermal changes. Pressure-energized designs provide additional sealing load during chilldown to ensure that sufficient contact force is maintained.

In upper-stage engines, rapid engine start after an extended coast period in space may be a requirement. Under these start conditions with cryogenic propellants, thermal transients will be experienced by valve assemblies as well as by other parts of the flow system. Dimensional changes momentarily may also occur in mating parts with similar coefficients of expansion or contraction. As a result of location in the valve, differences in heat-transfer rates, or small differences in mass, these parts may contract at sufficiently different rates to create misalignments or induce stresses sufficient to cause failure.

Misalignment of the poppet valving element and distortion of the seat are critical in metal-to-metal cryogenic poppet valves. Poppets with nonmetallic seals are more tolerant of thermally induced misalignment. The in-line poppet provides the best symmetrical design to minimize housing distortions from thermal effects. The 90°-angle poppet valve is the least symmetrical body design and requires greater design effort to provide uniform sections that minimize distortion.

Creep of materials subjected to cryogenic cycling can create permanent misalignments. Permanent distortions that occurred in the Saturn S-II stage butterfly prevalve resulted in complete seizure of the bearings after several months of intermittent cryogenic exposure. Cryogenic stabilization prior to final machining operations was required for dimensional control.

Materials that undergo phase changes at cryogenic temperature may grow and change dimensions permanently or may suffer degradation of surface finish. In a cryogenic butterfly valve, the drive shaft that served as the inner race for needle bearings was made of unstabilized 440 C material. Cryogenic cycling resulted in a change of phase of the material, caused the shaft to grow, and the shaft seized. Stabilized 440 C was utilized to correct the problem.

Some valves are exposed to gas-generator gases or thrust-chamber tapoff gases that may reach temperatures of 1400° F (1033 K). Such valves receive no preconditioning, and must be capable of operating reliably at room temperature, while subject to severe thermal gradients, and after temperatures have stabilized. Materials selected for the valve components have good high-temperature mechanical properties, are not subject to phase changes, and exhibit minimum creep. Materials such as Inconel 625 and 718 and Rene 41 have been used successfully in valves handling hot gases; Haynes 25 was used as the rolling-element material.

Diametral interference problems also may be encountered in hot-gas butterfly valves, since the disk will grow much more rapidly than the housing because of its small mass and its position in the hot-gas flow. Separate actuator housings are employed to provide a heat barrier so that conventional actuator materials can be used.

In valve assemblies subject to thermal distortion, journal bearings have been used where bearing loads are relatively low. Journal bearings usually will not seize, although friction loads may increase substantially. Self-aligning journal bearings can also be used to increase the tolerance. The prevalves, fill and drain valves, and recirculation valves on the S-II upper stage all employ journal-type bearings for butterfly drive shaft support. Journal bearings are usually less expensive than rolling-contact bearings, and fewer parts are used in the assembly.

2.3.5 Imposed Loads at Interface Mounting Points

Structurally, the valve assembly must be capable of transmitting external loads in addition to withstanding loads created by hard-line installation, loads from dimensional tolerances, loads induced by thermal transients, and vibration loads.

Stage propellant feed systems, especially in the large stages utilizing cryogenic propellants, normally employ numerous flexible lines and couplings to allow for thermal expansion or contraction of long sections of ducting. Some recent engine designs have used hard lines and thus required the ducts and valves in the engine feed system to carry structural loads; this practice saves weight by eliminating separate struts and mounts and also reduces the pressure drop through the feed system. Use of the valve assembly as an integral part of the engine structural members has been accomplished successfully in the F-1 booster engine, where the main propellant valves and hard lines provide support for the engine turbopumps. When structural loads are imposed on a valve assembly, the body housing and other load-carrying members such as flanges and caps must be designed to transmit the loads with minimum deflection and distortion so that valve operation is not compromised. Use of hard lines may also impose more severe vibration modes on the valve, and these loads must be accounted for in the design.

Cast housings can be used in valve assemblies of large booster engine systems if they are not part of the load-carrying structure of the engine. Die forgings generally are used for valve body housings that are mated with hard lines to form load-carrying structures and for the larger propellant-feed-system valves such as the S-II stage butterfly prevalves.

2.3.6 Environmental Factors

The valve assembly in a liquid rocket propulsion system is exposed to unique environments. During periods of storage on earth, the assembly is subjected to the earth environment and to vibration from transport of the vehicle; atmospheric moisture and sand and dust particles must be excluded from the assembly. During flight, the valve assembly is subjected to decreasing temperatures and pressures from the external environment. During engine operation, the valve assembly may be exposed to severe vibration modes and to steep thermal gradients from heat soak-back from the injectors and thrust chamber. Upper-stage engines are exposed to vibration modes both from the engines of the lower stages and from operation of the engines on their respective stages. Acceleration forces during boost and shock during stage separation may also pose design problems; however, in man-rated systems these forces are necessarily low. The space environment provides unique exposure conditions for the valve assembly: hard vacuum, solar radiation, meteoroid impact, zero-gravity conditions, and wide ranges of temperature. Extraterrestrial landing craft or probes will expose valve assemblies in the propulsion system to the environments of other planets, thus establishing another set of design requirements. A discussion of these environments can be found in references 33 through 35.

2.3.6.1 MOISTURE

The bearing and sealing surfaces of the rotary and reciprocating parts of a valve assembly can be damaged by moisture and resulting corrosion. Salt air exposure at the launch site, for example, was found to be a contributing factor to corrosion problems that arose in early development tests on the Titan engines. Although materials are selected for maximum corrosion resistance, the valve assembly design also includes positive design features to exclude moisture from the assembly. On cryogenic valves, positive seals are especially important because internal surfaces can condense air. Cryopumping can cause the internal pressure in the cavity that houses the linkage and actuator to decrease below the local atmospheric pressure and thereby produce an inflow of moisture-laden air; thus, these cavities must be sealed. During valve warmup, the cavity pressure may rise above local atmospheric pressure as the condensed gases vaporize or ice sublimes or melts. Thus, vent capability is also necessary. Vent port check valves (fig. 19) are used in such cavities to provide positive sealing and venting capability.

Desiccants have been utilized to protect packaged systems from moisture during transportation and storage; however, desiccant use in an operational valve assembly is limited. Desiccants require periodic inspection of some visual indicator device to assure their continued effectiveness. Such frequent inspections and possible frequent changing of desiccant cartridges has discouraged their use.

The exit of a valve such as a tank vent valve or a propellant duct bleed valve may require a protective cover to restrict the entrance of freezing liquids. This function often is provided by a suitably routed discharge line. A more compact solution is a cover designed as shown in figure 20; this design provides multiple noninterconnecting flow passages to prevent liquid from entering the valve cavity during rain.

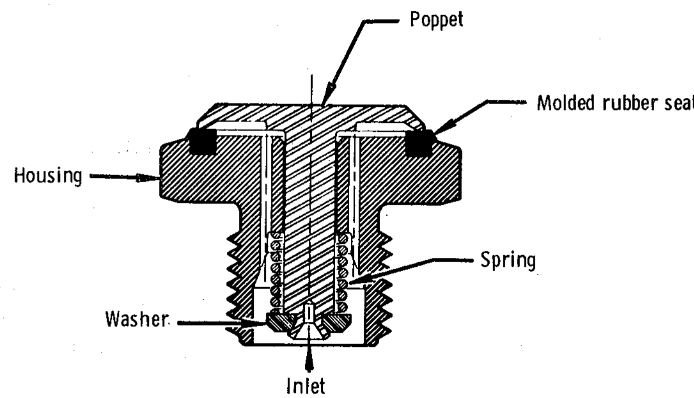


Figure 19. - Cross-section drawing of typical vent port check valve.

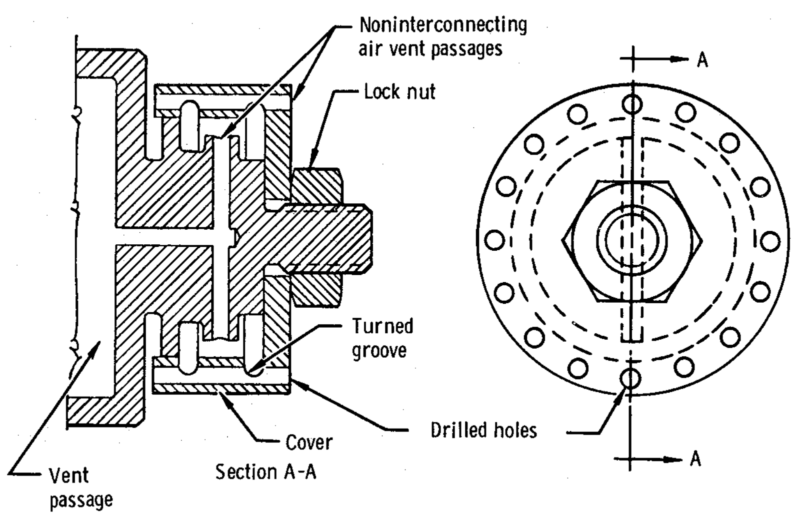


Figure 20. - Cross-section and top view drawing of rainhood assembly for vent line.

2.3.6.2 VACUUM

Special design provisions must be made when the valve is to be exposed to space vacuum. In interplanetary space, the gas pressure is approximately 10^{-16} mm Hg (1.33×10^{-8} $\mu N/m^2$); in near-earth orbit, the gas pressure is approximately 10^{-8} mm Hg (1.33 $\mu N/m^2$). Sublimation of metals in high vacuum and the effect of vacuum on plastics and elastomers used in a valve may pose problems. Conventional lubricants can be rendered unsuitable, and cold welding may occur in the hard vacuum environment. Information on designing for hard vacuum is presented in reference 36 and in section 13.6.2 of reference 4; references 37 and 38 present design information specifically for cold welding.

In upper-stage propulsion systems, valve leakage into a hard vacuum can result in propellant freezing as the liquid expands to pressure below its triple-point pressure. As a result, the propellant flow system can be clogged by frozen propellant. Extensive investigations of evaporative freezing have been conducted on the LMAE and LMDE systems, the Apollo Service Module propulsion system, the liquid-oxygen system for the J-2 engine (S-IVB stage), and the Gemini RCS and OAMS. References 23 through 25 present the results of the investigations concerned with valve leakage into a hard vacuum.

2.3.6.3 ACCELERATION, SHOCK, AND VIBRATION

The valve assembly is exposed to acceleration during powered flight, to shock from engine start and stage separation sequences, and to random and cyclic vibration from the rocket engine operation. In addition to these operationally imposed conditions, shock and vibration are induced by transportation and handling.

The design of valve components to withstand system pressures and impact loads from rapid valve actuation usually produces, especially for man-rated systems, component structures that can withstand the externally imposed acceleration, shock, and random vibration without complete failure or fracture. However, fretting of bearing surfaces, wear of shaft drive splines and square-end drives, particle generation from rubbing of nested helical springs, and valve element scuffing on the sealing surface are conditions that usually develop when valve assemblies are exposed to vibration.

The position of the valving element when subjected to peak vibration is important. First-stage valves are subject to peak vibration modes while in the open position, whereas upper-stage valves experience not only a lower vibration level, but one that is transmitted through stage structure at a time when the valve is closed. Acceleration loads from the lower stages and the shock of stage separation occur when upper-stage valves are in the closed position. When the upper-stage engine fires, the vibration occurs with the valve element in the open position.

Early butterfly valve designs exhibited wear of lip seals when the valves were subjected to vibration in the open position. This sealing surface degradation resulted in excessive leakage at shutoff. The off-center butterfly disk design provided a solution by allowing the disk to rotate free of the lip seal.

The poppet valving element may require special design precautions to avoid scuffing of sealing surfaces from vibration when the valve is in the closed position. One way to avoid such seat scuffing is to maintain a high seal load and keep the valve element mass to a minimum. Flexures may be used to prevent vibration-induced rotation of the poppet relative to the seat. Decoupling of the poppet from the actuator is another method employed to reduce the moving mass.

Although tested formulas exist for shaping components such as springs, shafts, and plates to avoid vibration problems, the more complex vibration-induced interactions of coupled valve components and other attached structures are not amenable to an analytical solution. For this reason, valve assemblies are subjected to severe vibration testing to confirm integrity of the design. In a new valve design, the random vibration environment often is not well established early in the program. Also, cyclic vibration from combustion instability may occur during the engine development phase and expose thrust-chamber main valves to severe vibration modes during static tests. The instability problem usually requires further testing to verify that the method used to solve the problem is correct. The thrust-chamber main valves are designed to withstand loads imposed by cyclic vibration to the extent that the valves themselves are not the weak link in the engine system.

Orientation of the valve and its placement in the engine area often are critical. The J-2 engine four-way poppet valve used on the pneumatic package functioned reliably on the engine; however, when the valve was utilized for control of the S-II stage prevalves, fretting of the metal poppet and seal caused excessive leakage. It was found that the valve had been located in an area of the vehicle where it was exposed to severe vibration; valve relocation reduced the vibration-caused seat damage. Vibration-induced damage also developed in flow sleeves in the valves on the F-1 engine gas generator. In the initial design, the sleeves were not firmly held along their entire length, and rubbing between the sleeve and housing resulted in the accumulation of metal particles in the flow passage.

A compact valve assembly envelope without unsupported projections of actuators and other attached components avoids amplification of imposed vibration. On the J-2 engine butterfly valve, electrical components located at the extremity of the actuator are exposed to 40 g, as compared with 10 g for the unprojected structure (fig. 21)). Damage to soldered pin connections of these connectors was difficult to prevent. Complete potting of the electrical connector provided the increased integrity required to survive in the more severe vibration environment.

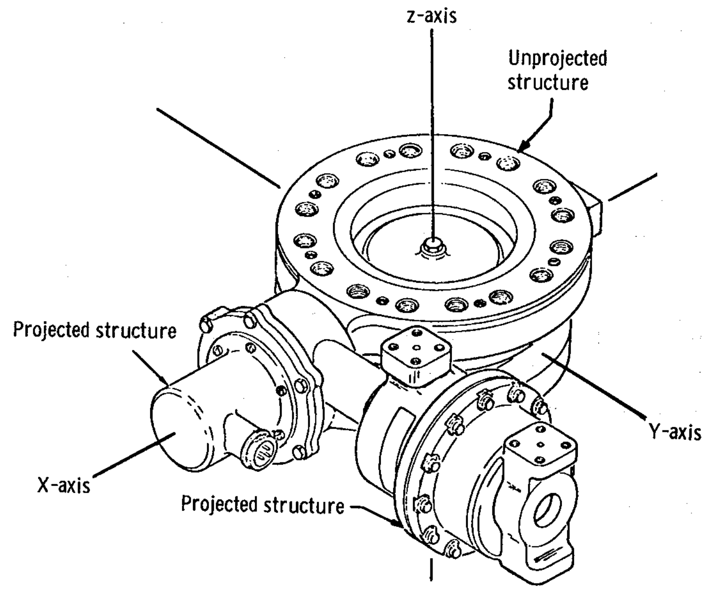


Figure 21. - Isometric drawing of valve projected structure susceptible to vibration amplification (J-2 butterfly main fuel valve).

2.3.6.4 RADIATION

Radiation in the space environment can, if sufficiently severe, cause changes in properties of nonmetallic seal materials and alter the properties of lubricants used in a valve. Manned missions usually avoid intense radiation zones; the propulsion system in unmanned probes may be required to function for extended times in a severe radiation environment. The radiation dosage that a particular valve assembly will experience during a space mission must first be conservatively estimated on the basis of the vehicle's flight path. Candidate materials for the valve are selected with the use of tolerance charts such as those presented in table 13.6.3.7b of reference 4. If adequate data are not available, tests are performed to establish the radiation resistance of the material. Since shielding is provided by the vehicle structure, other components of the rocket engine, the valve assembly housing, and other metallic detail valve parts, actual radiation dosage to the seal or lubricant is significantly reduced from the basic estimated value, and thus there is an implicit factor of safety in the selection.

2.3.6.5 ZERO GRAVITY

The valving unit operation in space cannot depend on weights, since the g-forces present in the earth environment that will, for example, close swing check valves are not present in the zero-gravity (zero-g) environment. The behavior of liquid in the valve during no-flow conditions will be different from behavior on earth; under zero-g conditions, liquid that does not wet the internal passage of the valve will contract to a spherical shape, and liquid that wets the internal passage will spread in a thin film. The thermal behavior of gases is altered, since there is no convection in the zero-g environment. Thus, the heat-transfer characteristics of the valve assembly will be different from the characteristics in the earth environment under which the valve assembly is tested. On the LMDE prevalve, the lack of convective cooling made necessary the design of a special bracket to provide a conductive path to a heat sink so that heat from a solenoid actuator could be dissipated (ref. 39). The zero-g environment also may influence the design of stage vent valves or auxiliary vent systems, since liquid as well as gas may vent overboard in this environment. The assured placement of a gas at the inlet of a vent valve, however, is not altogether a valve function. Use of propulsive vents to settle propellants in the tankage is the method employed on the S-IVB stage. This technique utilizes the vented gases to produce thrust axially along the stage and requires no special auxiliary systems to separate liquid from mixed-phase flow. Reference 40 contains a discussion of zero-g vent valves and auxiliary systems.

2.3.6.6 DORMANCY

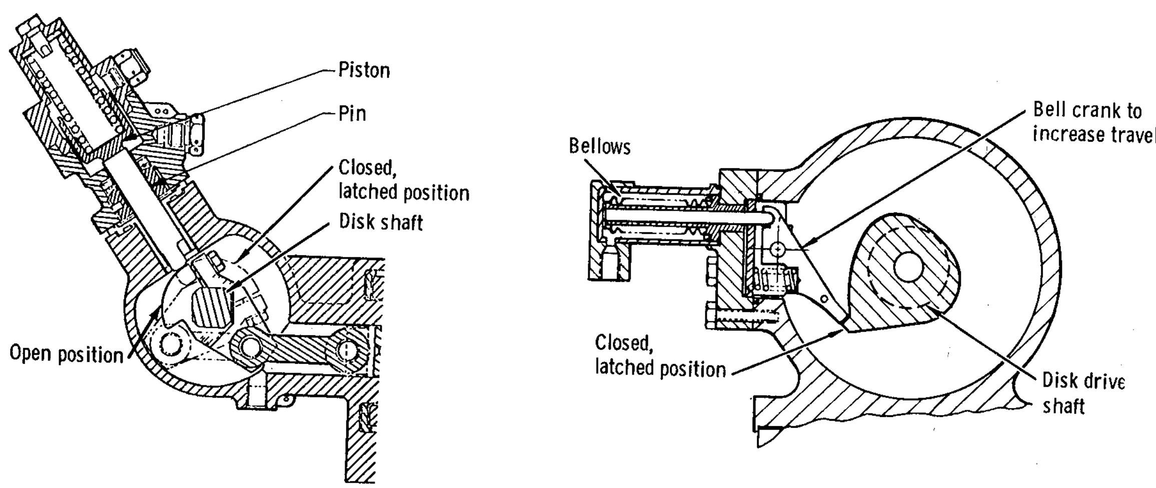
Exposure of the valve assembly to the space environment and to the local environment of the spacecraft for long periods of time without operation must be considered in the design of the valving unit and actuator and in the integration of the subassemblies. Periods of more than a year may elapse before the valve is called on to perform its function in the propulsion system. Nonmetallic materials may experience cold flow, swelling, and loss of properties due to radiation. Valve timing may be affected, especially on first actuation, because loss of O-ring elasticity and lubricity could require an increase in the force necessary to start motion. Properly selected low-friction long-life seal materials, combined with adequate margins on actuator force, are necessary to ensure reliable valve operation after dormancy.

2.3.7 Valve Latching

Latching mechanisms lock the valving element in a predetermined position. In small (1/4 to 1/2 in. [6½ to 13 mm]) solenoid-operated valves, magnetic latches enable a valve to hold position without continual energization. Also, permanent magnets have been utilized in small, normally closed solenoid valves to provide additional seating force in the closed position. In larger valves, the latch is a pin or detent positioned by a pneumatic or hydraulic piston or by a solenoid. The mechanism usually is incorporated into the actuator or the linkage between the actuator and valving element.

On the S-II stage prevalve, a latch provided for static testing holds the valve in the closed position should power be lost. The valve is utilized for emergency shutdown in static testing, and the latching mechanism is removed for flight. An early Atlas flight failure was traced to a latch used during static testing that engaged at launch and prevented the valve from opening. Static-test valve latches were removed from later Atlas vehicles to preclude the recurrence of such a failure.

Proper sequencing is important, and operational safeguards are established to ensure that the valve is not inadvertently actuated before the latch is released; otherwise, linkage may be distorted and the latching mechanism may be damaged. Figure 22 illustrates two methods for latching a butterfly disk.



(a) Piston-actuated direct-acting pin.

(b) Bellows-actuated latch.

Figure 22. - Cross-section drawings of latching mechanisms for a butterfly disk.

2.3.8 Filtering

Filtering of pneumatic and hydraulic supplies for engine control systems is accepted practice in all propulsion systems. Filters are also preferred in pneumatic actuator vent ports upstream of control orifices to ensure that the orifice does not become plugged. The rating of filters in pneumatic and hydraulic systems in some present propulsion systems is shown below:

System	Components Protected	Filter Rating
J-2 pneumatic-control package	Regulator and solenoid valves	10 μm
LMDE tank pressurization	Regulator and solenoid valves	15 μm absolute
LMAE tank pressurization	Regulator and solenoid valves	15 μm absolute

Filters also are used to catch the debris from explosive-actuated valves. Such filters are installed either integral with the valve in the downstream section of the housing or in the downstream line upstream of any critical components.

In present boosters, in which exposure of valves is relatively short and only one engine burn is required, filters generally are not employed in the propellant feed system; instead, reliance is placed on system cleanliness and filtering of propellants as they are transferred to the vehicle. Valves in such unfiltered systems must be tolerant of contamination.

In upper-stage vehicles and landing craft, where the propulsion system is designed for restart capability, or in reaction control systems with long coast periods between engine burns, leakage requirements are very stringent (on the order of 5 cm^3/hr helium). To ensure reliable valve operation and engine performance, filters must be provided. Filter selection is based on minimum clearances in the valve and the tolerance of the seating material; however, the filter micron rating is selected to provide an adequate margin of safety. For example, filter specifications for RCS engines in the 25- and 50-lbf (111 and 222 N) thrust range were based on minimum diametral clearances of 0.002 to 0.003 in. (0.05 to 0.08 mm) in the poppet guides. The 304C-mesh filters [10 μ (10 μm) nominal, 25 μ (25 μm) absolute] were installed integral with the valve inlet housing. However, valve sticking occurred, and it was necessary to expand the poppet guide (armature bore) clearances to 0.008 to 0.009 in. (0.20 to 0.23 mm) to ensure reliable valve operation. Filters for the LMDE feed system have a filtration rating of 40 μ (40 μm) nominal (60 μ [60 μm] absolute) and are located upstream of the quad-redundant valves. On the LMAE, the inlet filters for the quad-redundant propellant valve have an absolute filtration rating of 200 μ (200 μm).

The optimum filter for a given liquid or pneumatic flow system is dependent on (1) the largest particle size that can be tolerated by system components such as valves and injectors, (2) the amount of contaminant and the particle size of the contaminants that the filter must stop during the service life, and (3) the maximum pressure drop that can be tolerated by the flow system during its mission life. Detailed design information for filters is presented in reference 41. Filters usually are considered separate components; however, they are often incorporated into the body of a valve to reduce weight and envelope and to provide positive exclusion of contaminants from critical areas of the valve when the system is open. The benefit gained by filters in a flow system must be evaluated against the weight, envelope, and pressure-drop penalties to the system.

2.3.9 Purging, Draining, and Flushing

Incorporation of ports and fittings in the body housing of the valve assembly to purge, drain, or flush may be a system requirement as well as a valve requirement. Valve actuators may require special draining provisions if the actuation fluid is propellant and the control system utilizes a pressure-ladder sequence. On engine shutdown, the closing side of the actuator will be filled with propellant. All propellant from the closing-side actuator cavity must be drained, since any residual propellant remaining in the actuator will affect valve timing on subsequent valve operation. A pretest check to ensure complete drainage is made.

On the H-1 engine, erratic closing time on the thrust-chamber main valves was traced to residual fuel remaining in the closing side of the actuators. When the engine was vertical, drainage was complete. When the engine was gimbaled and thus tilted off the center line, residuals were not drained; these residuals caused the valve to close more rapidly on the subsequent test. Procedures were revised to ensure complete draining. The importance of locating the drain port or line to prevent trapping residuals in any possible engine position is evident.

In propulsion systems using toxic or corrosive propellants, draining or flushing is necessary to ensure personnel safety and reliable operation of the valve on subsequent tests. Although special fittings may not be included in a small RCS valve assembly, the valve assembly is flushed and purged through the valve inlet fitting to eliminate residuals after the valve is exposed to propellant. Special fixtures are used to hold the valve in the proper position, and the flushing or purging systems are maintained at acceptable cleanliness levels. These flushing and purging operations are a post-test procedure and are not part of the engine mission duty cycle.

On the LOX valve for the F-1 gas generator, an accumulation of water around the bellows used for loading the ball seats froze, and the resulting high seal load and friction affected valve timing. A routine vacuum-dry cycle on the engine bootstrap system was required to prevent condensed moisture in the system from accumulating in the valve.

System purges at engine start or shutdown may be directed through a valve housing, since the volume just downstream of the valving element often represents the extreme end of a line to be cleared of residuals. The orientation of the inlet or outlet port on the housing usually is determined by the position of the valve in the normal engine test position or position on the vehicle, because these ports often are located at a low point. On the main fuel valve in the early F-1 engines, ports were provided to water flush the engine to prevent buildup of deposits of sodium nitrate salts that resulted from the inert lead used in the thrust chamber on engine start; accumulation of these salts actually interfered with valve operation. On present F-1 engines, residual fuels are flushed by trichloroethylene directed through flushing ports on the main fuel valve.

2.3.10 Instrumentation

Instrumentation for the valve assembly usually is required for development testing of the assembly and for monitoring valve environmental exposure and performance during flight. In some instances, the instrumentation may be required as part of the engine sequence function or propulsion system function.

The reliability of the valve and of the control system in which the valve is utilized is enhanced when instrumentation necessary for system functioning and the instrumentation used for monitoring selected events are designed and installed so that a monitoring instrumentation malfunction cannot affect the proper functioning of the control system. The basic rule is that the addition of instrumentation for monitoring and information-collection purposes should not detract from or interfere with instrumentation necessary for functioning of the control system. For example, on the PU valves and HS butterfly valves on the Atlas vehicle, the "OPEN" and "CLOSED" position-monitoring instrumentation is separated from the position instrumentation that is required for functioning of the closed-loop servo control system on these valves. The disadvantage of one switch serving both purposes is that the functional and monitoring systems become interrelated at that switch. A malfunction in the monitoring instrumentation system could adversely affect the functioning switch for successful completion of the mission. Although a dual system adds to the complexity of the valve design, it eliminates possible interaction. Reliability of the control system is enhanced also when the instrumentation is designed with provisions to ensure that structural or operational failures do not interfere with system functioning. This "fail-safe" design philosophy, for example, may ensure limited flow from a pressure-sensing line should the line, bellows, or diaphragm fail. By limiting flow, the potential of explosion or fire is reduced, damage to surrounding equipment from outflow of cryogenic fluid is minimized, and system pressure loss is minimized.

Instrumentation requirements based on the objectives of minimizing interaction of monitoring and functional instrumentation and providing a fail-safe mode should be established early in the valve design; in this way, passages for pressure and temperature taps and position instrumentation can be integrated into the valve design. If monitoring instrumentation is not required for flight, the valve design can include provisions for installation of a separate instrumentation package for ground checkout tests only. The following sections review the various valve assembly instrumentation systems, problems encountered, and solutions to those problems; the sections do not describe in detail the state of the art in the design of individual pieces of instrumentation.

2.3.10.1 INTERNAL PRESSURE

Pressure instrumentation for valve assemblies may be required for development testing, for acceptance of the valve, for checkout of the valve in the field, and in some cases for flight instrumentation. A description of the state of the art in pressure sensing in valve actuation systems is contained in reference 12. Pressure measurements of the fluid flow stream controlled by the valve generally is a requirement only during development testing. Points of measurement usually are located in upstream and downstream spool sections that are mated to the valve assembly during flow tests. Location of such taps is discussed in section 15.5.5 of reference 4.

2.3.10.2 VALVING ELEMENT POSITION

The following types of position indicators have been utilized in operational valves:

- microswitch
- magnetic-reed switch
- variable-resistor switch
- wiper contacts
- variable-reluctance unit

Microswitches have been utilized on the Atlas butterfly main valves and also on the LMAE bipropellant valve. Problems associated with the use of short-stroke microswitches to give "OPEN" and "CLOSED" information result primarily from the lack of overtravel. When the switch bottoms out, any further shaft movement will transmit excessively large forces to the switch assembly and mounts. Use of flexible mounting can result in vibration problems.

Magnetic-reed position-indicating switches are utilized on the LMDE bipropellant valve (fig. 23). Major problems have been burning or fusing of contacts and failure of the switch to actuate because magnetic force available for actuation was marginal (ref. 39).

Position-indication devices used on J-2 engine butterfly valves and J-2S engine ball valves have employed a rotary-resistor switch assembly that provides, in addition to "OPEN" and "CLOSED" indications, a valve position trace. The variable-resistor unit used in the J-2 engine main valves is shown in figure 24. Problems of linkage adjustment and loosening of set screws have occurred with the variable-resistor unit, and the wiper and resistor element contacts are sensitive to vibration. The switches are hermetically sealed to avoid moisture

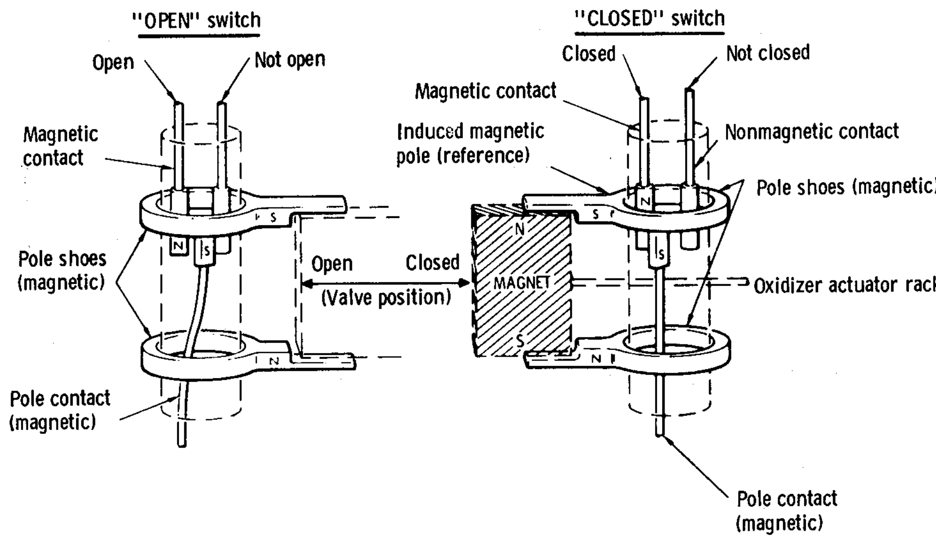


Figure 23. - Schematic drawing showing operation of magnetic-reed position-indicating switch on LMDE bipropellant valve.

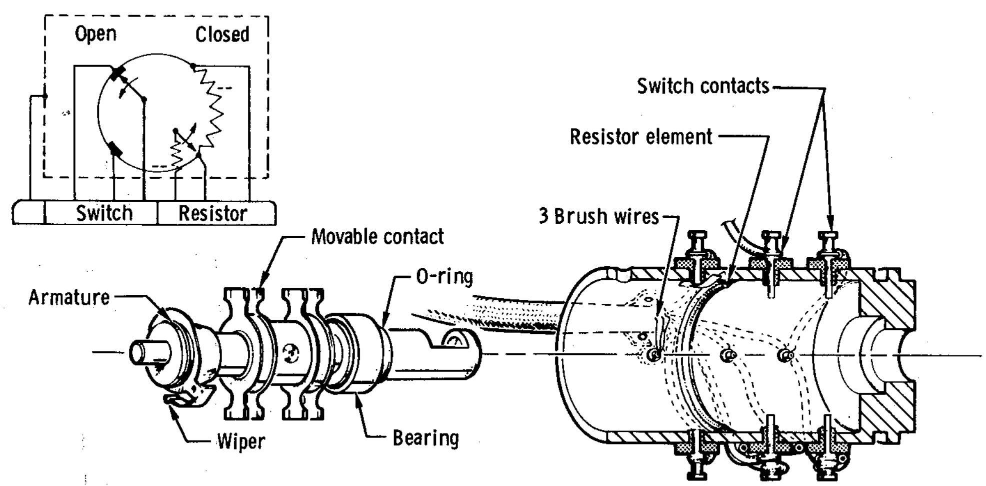


Figure 24. - Cutaway drawing of rotary-resistor position-indicating switch (J-2 main valves).

problems. Poppet valves on the F-1 engine employ rotary-resistor switches and linear switches. Use of the rotary switch involves additional linkage to convert the linear motion to rotary.

The most accurate position indicator is the variable-reluctance unit used on the Atlas PU valve, which is used as part of the closed control loop for this butterfly valve. Although this indicator is accurate, its weight, complexity, and possible electromagnetic signal interference must be evaluated.

Location of the position-indicator switch assembly is a factor in avoiding erroneous indication if the shaft or linkage fails. On ball and butterfly valves the indicator ideally is on the idler shaft. On blade valves, the indicator is best on the opposite side of the blade from the crank drive shaft. Although such locations are preferred, envelope restrictions and sealing problems can dictate use of other locations.

Additional state-of-the-art information on position-indicator devices is contained in reference 12.

2.3.10.3 TEMPERATURE

Temperature is monitored in propulsion system valve assemblies usually during environmental tests and development tests. In some cases, temperature-measuring instrumentation may be required for flight monitoring of propellant temperatures to determine when a particular portion of the feed system reaches a required temperature. Instrumentation to monitor flight temperatures was used on the J-2 engine bleed valves; these probes had a flange connection, because they penetrated into the valve propellant cavity. Although temperature probes for development and environmental tests usually are applied to the valve assembly external surfaces with tape or adhesives, development tests may dictate that the probe penetrate to areas on the interior of the valve. Special temperature probes may have threaded connectors and springs to push the probe against the bottom of the penetration cavity, or the probe may have the thermocouple wires pushed into a drilled cavity and cemented in place with epoxy resin. If the thermocouple penetrates into a propellant cavity, the material in the probe and in the connector and seal must be compatible with the propellant.

The thermocouple design can be critical. For example, in development tests where housing temperatures were being measured to determine transient temperature effects, the mass of a special screw-type probe and the remote location of the junction relative to the contact tip caused the time constant of the thermocouple to exceed the span of the transient effect being monitored; transient temperature extremes were not measured. Accurate direct measurement of housing temperatures on large valve assemblies during environmental tests is especially important in avoiding misleading results. Many hours may be required to reach stable internal temperatures. The use of indicators such as the cessation of active bubbling of a liquid-nitrogen bath in which the valve has been immersed can lead to large errors. On a large valve, it was found that the time required to reach a stable internal temperature was 45 minutes, about twice as long as the elapsed time to cessation of active bubbling.

2.3.10.4 ACCELERATION

Vibration testing of valve assemblies during development and qualification requires the attachment of acceleration-measuring instrumentation to the valve body and to various valve subassemblies. The accelerometers usually are attached with epoxy resin. Occasional attachment problems occur when the particular valve design does not provide for convenient attachment at locations where maximum accelerations occur as a result of amplification of the input vibration. If vibration testing is conducted at cryogenic temperatures, attachment problems are compounded; therefore, provision for mounting points are best made during the valve design phase.

2.3.10.5 STRAIN

Strain gauges are utilized during development tests for proof testing and for burst tests of the valve assembly. Strain gauges usually are attached with epoxy resin. Problems have occurred when an attempt was made to install a strain gauge in an internal valve port. The strain gauge and wire had to be attached to the detail part, then assembled in the valve; the fine wire leads broke frequently, and extreme care was necessary during the assembly operation. Dial-indicator strain instrumentation is not well adapted for proof and burst testing, since direct viewing is not desirable; however, such instrumentation can be used in conjunction with photographic coverage that provides a record of the dial readings during the test.

2.3.11 Valve Sterilization

Sterilization of the propulsion system of which the valve is a component part dictates that the valve assembly design be capable of withstanding the effects of elevated temperatures and sterilization fluids. In storable systems, elevated temperatures can increase corrosion rates. Exposure of explosive-actuated valves to elevated temperature may change the sensitivity of the explosive charge and require that higher amperage be used after sterilization to ensure firing. The high temperature (nominal 275° F [408 K]) may also cause binding because of thermal expansion of parts in the valve assembly. Reselection of some nonmetallic materials may be necessary after the effects of sterilization have been assessed.

2.3.12 Tolerance Stackup

A well-executed tolerance stackup can avoid interference problems that can occur during initial assembly of components of the valve. Layout of the valve components and subassemblies at ten-times scale also has been employed to uncover interference problems. Besides displaying physical interference problems, the stackup of tolerances may reveal excessive clearances that can cause misalignments resulting in functional failure and possible shortening of component life. Tolerances on length, diametral concentricity, and angular dimensions require thorough review. Two examples indicate the more obvious effects of improper tolerances and dimensions:

(1) During the first assembly of a prototype butterfly valve, the bolts holding the disk to the drive and idler shafts were found to strike the valve housing when the valve was actuated. The inner contour of the housing required additional recessing to provide adequate clearance.

(2) An outer bearing race could not be pressed fully into place. Inspection revealed that the radius at the bottom of the race bore was larger than the bearing manufacturer's specification allowed.

These examples show the need for a stackup of dimensions and tolerances of components of the valve assembly as an important final review of the valve assembly design before release of the detail drawing for fabrication.

2.3.13 Preventing Misinstallation

Prevention of misinstallation is a concern that applies to assembly of components in the valve as well as installation of the valve in the propulsion system. If a particular part will fit more than one way, it is probable that at some time during production or service it will be misinstalled. For example, a ball valve failed in functional test because of excessive leakage past the ball seal. Disassembly of the valve revealed the Kel-F ball seal had been installed reversed. On this assembly operation, the technician had been required to distinguish between a 30° angle and a 45° angle. The seal was redesigned to make the surfaces less identical, thus eliminating the possiblity of an erroneous "eyeball" estimate of the proper angle for seal assembly direction.

To prevent such problems in aircraft, military specifications require that directionally critical components be designed to prevent reverse installation. Similar precautions are followed in the design of própulsion system valves so that misassembly is difficult if not impossible. On mating parts with bolt hole circles, an unsymmetrical hole pattern is a good method to ensure proper alignment. Mating parts may also be keyed, aligned with steel dowels, or provided with a tab. Push rods are designed to fit only one way unless rod ends can be made identical. Line-mounted valves in particular are prone to reverse installation. Pneumatic and hydraulic connections to the valve actuator are subject to misinstallation, especially if flexible lines are used. On hard-line engine control systems, the requirement can be relaxed, because the prior fabrication of hard lines in accordance with detailed drawings makes misinstallation difficult. In such cases, the angular separation of the inlet or outlet ports is a good method to prevent misinstallation.

Unsymmetrical hole patterns that ensure that components of the valve assembly are rotated to align only with a designated orientation dictated by engine envelope obstructions can result in too much constraint early in design of feed system components. During engine development, such envelope constraints can change, and rotation or reclocking of various valve subassemblies may be required. In the early development phase of the J-2 engine feed system, rotation of an entire main valve assembly reduced downstream turbulence.

2.4 ASSEMBLY OF COMPONENTS AND FUNCTIONAL TEST

Buildup of the valve assembly from the component parts is a step-by-step operation in which well-documented procedures can eliminate assembly errors. To provide a record of the assembly steps, a log on each valve is maintained by serial number; the log contains a record of critical dimensions, angles, and the results of leak and timing tests. Subassemblies such as actuators, sequence valves, compensation timing orifices, and check valves require separate functional testing before installation, so that there will be little reason to disassemble the valve and rebuild it. It may be necessary for the valve designer to provide fixtures and gauges to assist the technician in assembling critical components and to verify proper assembly. Burst tests conducted in a "hazard" test cell are used to confirm calculated burst pressure for the valve assembly; such tests are made before any functional tests involving pressure. Prior to leak tests, the valve assembly is proof tested in a hazard test cell.

Functional tests may include cycling of the valve, timing tests, and valve leakage checks. These tests are designed both to verify proper assembly and to check for flaws in fabrication of valve components that may not be detected with inspection techniques available. For instance, a cycling requirement was stipulated for a butterfly valve when it became apparent that inspection techniques could not be relied on to screen out actuator rods having surface flaws. A 50-cycle functional test after assembly eliminated discrepant parts.

2.4.1 Lubrication

Lubricants are used in valve assemblies primarily for reducing friction; other benefits gained are enhanced corrosion resistance and reduced leakage on static and dynamic O-ring seals. Control of type and quantity of lubricants used in valve assembly areas is critical.

Excessive application of petroleum-base grease on O-rings used in the actuators of the HS and PU valves on an Atlas engine led to failure of the servo system. The excessive grease formed globules in the hydraulic system; the globules lodged in the filters of the servo valve, restricting flow and altering system pressures.

On the Atlas MA-5, Thor MB-3, and Saturn H-1 engines, DC55 was used to lubricate the shaft bearings of the main fuel (RP-1) butterfly valve, while the identical bearings in the main oxidizer valve were assembled dry. A detonation in the bearing cavity of an oxidizer valve was traced to use of a lubricated bearing instead of a clean bearing. Inadequate inspection was the cause of the substitution. Inspection was made difficult since the bearing had a full complement of needles retained in the outer race. Loose needles without retainers, which are assembled individually to make up the bearing, are also employed, and such bearings can be readily inspected to ensure cleanliness.

Valve linkages and shaft square-end drives on butterfly and ball valves have been lubricated with dry-film lubricants to prevent fretting. For oxidizer service, a sodium silicate-bonded inorganic dry film has been used; for fuel valves, a resin-bonded dry-film lubricant. Even though the linkage cavity may be sealed from the oxidizer flow stream, leakage could result in an oxygen-enriched atmosphere, and compatible lubricants must be ensured.

Film adherence to the surface of the base metal is important. Flaking has resulted in lip-seal damage. In small solenoid pneumatic valves, sliding surfaces such as the solenoid plunger and poppet guides use dry-film lubricants. Flaking in these small valves can cause galling and excessive friction that will affect valve timing.

For some lubricants, exposure time is critical. A fluorosilicone lubricant compatible for a short term with inhibited red fuming nitric acid (IRFNA) was used for O-ring lubrication in a thrust-chamber main valve. An upstream burst disk provided isolation and prevented exposure until engine operation. On tests with no temperature conditioning, the valve was decontaminated immediately. On cold tests, decontamination was delayed; the lubricant base reacted with the IRFNA, and the filler material in the lubricant settled out in the valve clearances. After several such tests, the valve became inoperative because the poppet jammed.

Chlorinated biphenol often has been used in linkage cavities to protect sliding surfaces from corrosion. On J-2 engine valves, where actuators are exposed to cryogenic temperature, excessive applications of this material froze in the rod bore and prevented valve actuation. Use of chlorinated biphenol in valve linkage cavities was discontinued.

Materials such as perfluoroalkyl polyether and fluorinated tributylamine oil have been used for lubricating sliding surfaces and O-rings in storable-propellant valves. The polyether is a grease-type lubricant that does not easily wash away. It is compatible with hydrazine compounds and oxides of nitrogen; however, it may detonate if used to lubricate aluminum dynamically. In the LMAE valve package, both lubricants are used for parts exposed to propellants.

Small RCS engine valves with critical clearances on the plunger and poppet guide are not lubricated. Although chlorinated biphenol has been used on threaded fittings on these small valves, final assembly is dry so that possible contamination of internal parts is avoided.

2.4.2 Contamination Control

After fabrication, parts of a valve must be cleaned and packaged to protect them from contamination and from damage to critical surfaces. The individually packaged detail parts are opened only when they are needed for a particular assembly operation. The cleanliness level required in the valve assembly area is based on the critical clearances in the assembly, orifice sizes, and the particle sizes that a valve element seal can tolerate. Small valves such as the propellant valves for the SE-8 engines require a clean-room valve assembly area having the following controlled environment:

Particle size, μ (μm)	Particle concentration		Maximum number of particles of all sizes	
	per cu. ft.	per cu. m	per cu. ft.	per cu. m
5 to 65	≤ 200	7062	200	7062
over 65	≤ 10	353		

The temperature is maintained at 70°±10° F (294±6 K). The working environment is monitored each working shift.

Small pneumatic and hydraulic control-system valves require similar clean-room assembly areas, with conditions based on the particular valve clearances, seat contamination tolerance, etc. Laminar-flow benches such as specified in chapter 5 of reference 40 are used in valve assembly clean rooms to provide clean work bench areas for valve assembly. Larger valve assemblies such as propellant main valves for booster engines have less critical clearance problems and are more tolerant of contaminants on the seating or sealing surfaces. To ensure reliable operation, however, such valves are assembled in a controlled environment.

Contamination generated during the assembly operations is almost impossible to predict. For example, flaking of electrolytically plated nickel on a blade valve drive spline was found to be the cause of premature wear-out of the Kel-F blade seal. The flaking occurred during the initial cycling required to set the microswitch position indicators. The assembly operation was changed to allow a final cleaning step before the valve cavity was sealed. Similar instances have occurred when burrs on individual valve components were broken off during assembly or valve actuation and contaminated the valve assembly. The solution was the examination of every component under 10X magnification prior to assembly to distinguish between firmly attached and weakly attached burrs (fig. 25). This preassembly

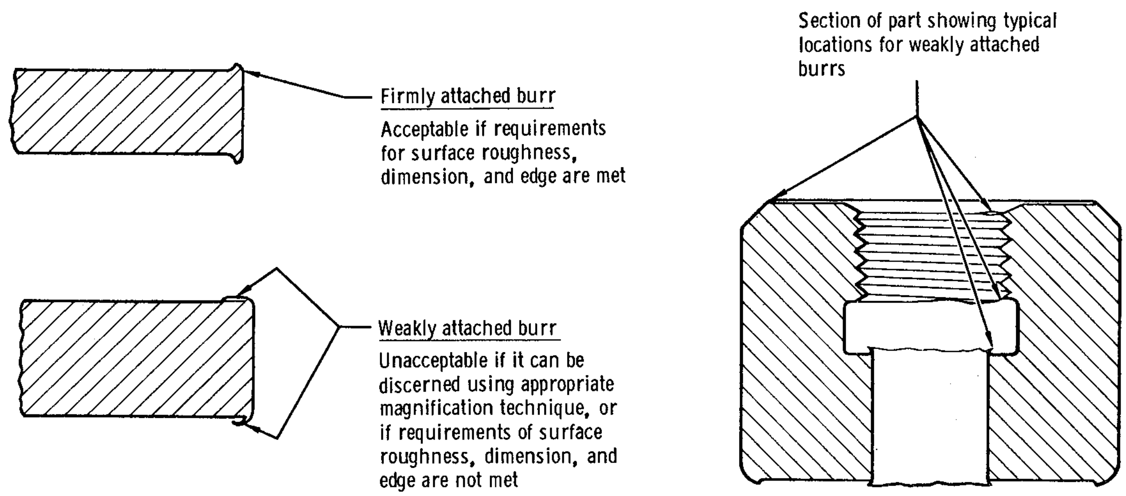


Figure 25. - Guide for inspection of burrs on machined valve components.

inspection procedure significantly reduced malfunctions caused by contamination of RCS valves. In the four-way pneumatic control valve for the J-2 engine, metallic seals require that the poppet stackup be held to a length tolerance of ±0.00005 in. (±1.27 μm). Special care is taken during assembly of this valve to avoid trapping dust or other contaminants between the mating surfaces.

After a valve is assembled, flushing operations and particle counts are employed to check the cleanliness of the valve flow passage; however, such flushes cannot be relied upon to remove all particles, and some may remain lodged in the assembly. Small RCS valve assemblies such as those for the SE-8 receive a final flush of trichlorotrifluoroethane. A 100 cm^3 sample is taken and analyzed to confirm the following cleanliness level (applicable to an SE-8-class valve):

Particle size range, μ (μm)	Number of particles per 100 cm^3
<10	*
10 to 25	<100
25 to 50	<20
50 to 100	<5
>100	0

*Not to be counted, but no slurry of fine particles that covers an estimated 5 percent of the total effective filter area shall be allowed.

Figure 26 shows the particle count limits and data for RCS propellant valves (ref. 13). Also plotted is the plunger armature clearance for these valves which, together with the seat, represents the critical contamination-sensitive areas of these valves.

Lines connected to the valve for flushing or proof testing or other check-out operations are kept free of any contaminants. Hydrocarbon contaminants from thread lubricants on hose fittings can clog small orifices and jam clearances in a valve.

Protective closures are used on ports and flanges of a valve assembly to maintain cleanliness until the next assembly operations. However, care must be exercised that closure design and closure use preclude inadvertent installation. A failure during static firing of the S-1C vehicle was found to have been caused by inadvertent installation of a duct flange closure. A transparent plastic film material had been used to maintain cleanliness until the duct was installed on the vehicle. The transparency of the film, which allowed the material to assume the color of the flange, precluded detection of the film in the assembled flange. To prevent such assembly errors, closures are controlled and closure designs are well documented. A common practice is to use a special closure color to signify non-flight hardware and to make the closure at least 0.125 in. (3.18 mm) thick. On the J-2 engine, the color red is utilized for closures and a "hat"-shape cross section is utilized to increase the visible thickness of the closure. Closures also provide sealing surface protection and external thread protection.

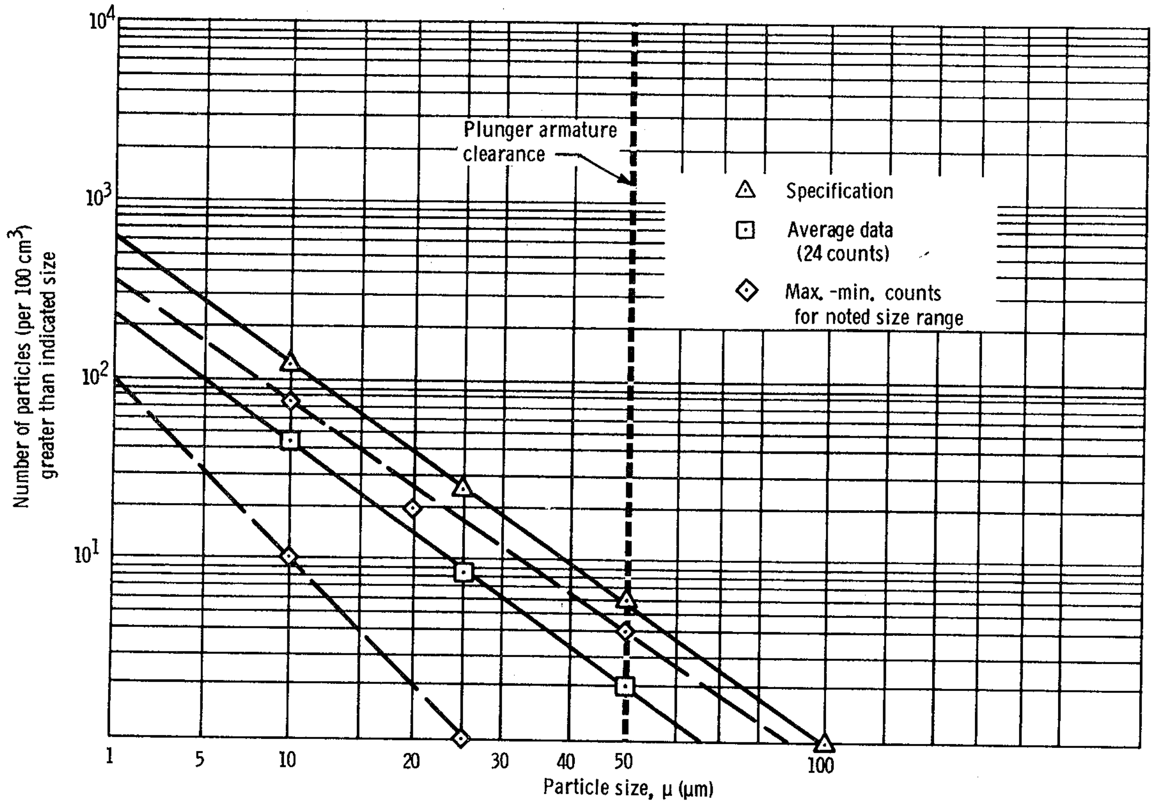


Figure 26. - Particle count data and specified limits for RCS propellant valves (ref. 13).

Desiccants are employed to protect valve assemblies from moisture. If the valve is small, the entire valve is placed in a plastic bag and desiccant is used in a second outer bag to prevent the entry of moisture to the valve. On larger valve assemblies, special flange closures that incorporate a compartment for holding the desiccant are used. The plastic closures utilize neoprene gaskets to provide sealing with surfaces of the valve. Silica gel is packaged in nylon bags that have been impregnated with plastic. The bag must be sturdy enough to withstand transportation vibration and handling, so that the contents are not spilled. Early experience with desiccant bag material had shown paper to be a poor selection. Desiccant bags made of paper were torn, and the valve assembly was contaminated.

2.4.3 Purging and Flushing

After a valve assembly is exposed to propellants, it must be purged or flushed to eliminate residuals. Such residuals can form corrosive substances that cause damage to the valve assembly software and metallic materials. Nitrogen tetroxide residuals can combine with very small percentages of water (0.1 to 0.4 percent) to cause a significant acceleration in the corrosion rate of a normally compatible material. The toxic nature of many storable propellants makes their elimination from the valve assembly important for the safetv of personnel subsequently handling the valve. The butterfly main valves on the Titan III engines employ Kel-F lip seals that must be flushed after N_2O_4 exposure to maintain adequate physical properties for 18 months of service. Valve refurbishing is required after 30 days if the valve is not decontaminated.

The Teflon seals in small RCS thruster valves are degraded by exposure to N_2O_4; however, because of the captured seal design, the loss in strength is not critical if the valve is properly flushed. On N_2O_4 valves, trichlorotrifluoroethane or trichloromonofluoroethane is used as the flushing fluid. In storable propellant fuel valves, these materials cannot be used if MMH is present, because the sludge formed can cause the valve to stick and become inoperative. Isopropyl alcohol is the preferred flushing fluid for hydrazine compounds. Purging and vacuum dry cycles are used to ensure complete removal of the flushing agent from the valve assembly.

Flexure tubes on a small dc-torquemotor-operated poppet valve were severely attacked when the methylene chloride in the system used to flush the valves became contaminated with water. Residuals that remained in the valve after flushing operations attacked the metal and resulted in sufficient loss of strength to cause the tube to fail when exposed to normal engine shutdown pressure surges. Figure 27 shows a section through the failed tube; note lack of corrosion on outside surface of sleeve. Water contamination has been a source of numerous problems in small RCS valving.

Reference 42 contains a discussion of the use of phosphoric acid for flushing small RCS propellant valves. Valves with erratic timing or sticking problems due to contamination were returned to reliable operation by phosphoric-acid flushing. In the oxidizer valves, solvated iron nitrate in the nitrogen tetroxide can precipitate in the valve and accumulate in the plunger armature clearances. The phosphoric-acid flush removes this contaminating material. Phosphoric acid flushes were also found beneficial in fuel valves showing erratic timing. After screening tests, the choice of the phosphoric-acid solution evolved to the formulation by volume percent as follows:

Phosphoric Acid	25±1
Wetting Agent (Triton X-100 or equivalent)	0.1±0.05
Methyl or Isopropyl Alcohol	74.9±1

Figure 27. - Photomicrographs of flexure - tube corrosion caused by water-contaminated methylene chloride decomposing to hydrochloric acid.

After engine operation, a purge may be part of the shutdown sequence. Purges to remove residuals from the lines after shutdown usually enter the flow system just downstream of the thrust chamber main valves. In storable systems using N_2O_4 and N_2H_4, an inert gas purge may be considered as a means to clear the downstream portions of the valve, lines, and injectors so that crystalline deposits cannot form in the valve and lines and later damage valve seats. Downstream ball seals on the LAME and the AJ10-137 engine bipropellant valves have been damaged by such deposits (ref. 43). Similar deposits occurred on the oxidizer seals of the bipropellant ball valve.

2.4.4 Qualification Testing

To ensure that the new valve design will operate reliably in the propulsion system, the valve assembly undergoes qualification. The component qualification normally exposes the valve to the temperature extremes expected in service, burst tests to ensure the integrity of the design, internal and external leakage tests, actuation tests, endurance cycling tests, tests in hard vacuum, acceleration tests, and vibration tests. The tests and combinations thereof are designed to expose the valve to an environment at least as severe as that experienced in normal operation; unrealistic overstress conditions are avoided. Failure of the valve to pass certain portions of the qualification test is not necessarily grounds for immediate redesign of any particular component. The exact failure mode is established before corrective action is instituted. Further testing then may be required to ensure that the course of action is correct.

2.5 ENGINE, STAGE, AND SPACECRAFT CHECKOUT

The greater portion of valve assembly cycle life is spent in valve checkout operations, static engine tests, and stage checkout tests, rather than in actual engine firing time in the mission. Table VIII shows the estimated number of cycles required for the J-2 three-way and four-way solenoid valves in the pneumatic control systems from the time of first installation on the J-2 engine pneumatic package until the final checkout (Countdown Demonstration Test) is completed at the Kennedy Space Center (KSC) before launch. Engine operation on the S-II stage requires these valves to be energized and de-energized one time. On the S-IVB stage, two cycles are required on a normal mission.

Monitoring of test and checkout operations is necessary to ensure that the valve assembly is not exposed to more severe conditions than the valve is designed to withstand. Such conditions may result from excessive pressure, high temperature from rapid pressurization through the facility pressurant supply, propellant transfer line surge pressures associated with rapid valve closing, long energizing times on solenoids, excessive valve actuations due to repeated tests, and methods used to checkout engine clusters or booster stages. The results of the monitoring may be either a reassessment of the valve requirements or, preferably, a change in the procedures that expose the valve to conditions that exceed the design limits.

On the LMAE valve package, checkout operations included valve actuator leak checks that were accomplished by actuating the normally fuel-actuated valve with helium and then performing the leak check with the actuator pressurized. During this checkout test, excessive leakage on some valves was traced to a twisted O-ring in the valve actuator. The twisting occurred because of rapid actuation. An orifice was installed in the helium supply line to slow the valve actuation during the checkout test. Although it was shown that the O-ring selected for the application was a contributing factor to the twisting, checkout procedures were revised to eliminate the severe checkout test mode.

TABLE VIII. – Estimated Maximum Number of Checkout Cycles on Three-way and Four-way Pneumatic Solenoid Valves on the J-2 Engine

Checkout test and Facility	Number of solenoid actuations					
				Three-way helium control		
	Three-way emergency vent	Four-way ignition phase	Four-way mainstage control	During fill*	After fill*	Dry cycle**
J-2 engine checkout (S-II)						
Rocketdyne (Canoga Park)	65	25	25	25	32	15
Rocketdyne Field Lab	15	45	45	0	36	9
S-II stage checkouts						
NAR Space Div. (Seal Beach)	34	22	22	66	88	39
Michoud Assembly Facility	55	33	33	39	59	25
Kennedy Space Center	26	26	26	0	55	15
Total	195	151	151	130	270	103
J-2 engine checkout (S-IVB)						
Rocketdyne (Canoga Park)	65	25	25	25	32	15
Rocketdyne Field Lab	15	45	45	0	36	9
S-IVB stage checkouts						
McDonnell-Douglas (Huntington Beach)	11	40	40	88	66	39
McDonnell-Douglas (Sacramento Test Operations)	60	25	25	45	77	30
Kennedy Space Center	22	10	10	0	77	19
Total	173	145	145	158	288	112

* Pressurized

** Unpressurized

3. DESIGN CRITERIA and Recommended Practices

3.1 VALVE SELECTION

The valving unit design shall reflect systematic consideration of all factors involved in the intended valving application.

Because the final valve selection will be a compromise, with only the most salient factors providing the real margin of difference, rate the candidate valving element types on the basis of the considerations listed below. The factors listed have not been placed in order of importance. A matrix such as that shown in Table IX can be used in combination with a method of rating those considerations that cannot be given quantitative expression.

Basic Factors

Reliability
Sealing capability
Differential pressure (ΔP) (penalty to system)
Size, weight, and envelope
Compatibility of materials with service fluids
Cost

Performance Characteristics

Stability
Stroke versus flow area (primarily in throttle valves)
Actuation control time
Timing (repeatability)
Downstream flow profile
Penalty for preferred position (fail-safe position)
Cycle life

Resistance to Malfunction from

Seal leakage from contamination or minor blemishes on sealing surfaces
Galling
Distortion
Vibration
Pressure surges
Freezing
High differential pressure

TABLE IX. – Concluded.

Consideration	Point value per candidate[1]		
	4-in. (10 cm) poppet	3-in. (7.6 cm) ball	4-in. (10 cm) butterfly
F. Time required for			
Design	4	3	4
Development	3	3	4
Manufacture	4	3	4
Service	3	3	4
Subtotal	14	12	16
Total	89	81	90 [2]

[1] 5 pts - most desirable
1 pt - least desirable

[2] Point total shows preference for butterfly valve as thrust chamber main valve.

3.1.1 Flow Characteristics

A shutoff valve shall exhibit minimum pressure loss and shall have minimum envelope dimensions consistent with the application. A throttling valve shall satisfy criterion 3.1.8.

Use flow coefficients such as those listed in table II to establish the basis for comparison of flow characteristics of candidate valving units.

Although poppet valves usually exhibit higher pressure losses than the butterfly or ball valves, the following mitigating factors should be considered relative to use of the poppet valving element:

(1) In line sizes less than 2 in. (5.1 cm), the increased area required to reduce the pressure losses in the poppet will not cause a large percentage increase in weight or envelope.

(2) An angle poppet may replace a 90° elbow that would otherwise be required if an inline valve were used, thus reducing the pressure drop normally associated with an elbow plus a valve.

(3) In large (8 to 10 in. [20.3 to 25.4 cm]) lines and at pressures as great as 2000 psi (14 MN/m^2), a partially balanced poppet will reduce actuator requirements and overall valve envelope.

(4) In small multipassage pneumatic and hydraulic control valves, a balanced poppet can reduce actuator requirements and valve size. Pressure losses associated with the poppet can be minimized by full porting so that flow areas are larger than the inlet fittings.

(5) Empirical development of poppet and passage contours can significantly reduce pressure drop; however, the process is expensive both in terms of test time and machining time to generate special contours.

The butterfly valve is not recommended for service pressures above 2000 psi (14 MN/m^2), because the increased thickness of the disk and large shaft diameters required to withstand these pressures will result in reduced flow area. At lower pressures, the butterfly valve exhibits the optimum flow characteristics, especially in the low-pressure range (less than 250 psi [1.72 MN/m^2]), where disk thickness and shaft size occupy only a small percentage of the flow area; butterfly valves therefore are recommended for low-pressure service in line sizes from 2 to 10 in. (5.1 to 25.4 cm). In line sizes below 2 in. (5.1 cm), the butterfly valve should not be considered, because the disk and shaft again occupy an increasing percentage of the total flow area and reduce the flow coefficient. Use the butterfly valve when short face-to-face dimension is important.

Use the full-ported ball valve when minimum pressure loss and little downstream flow disturbance are of major importance. Optimum ball valving element sizes are 1 to 3 in. (2.5 to 7.6 cm) for moderate pressure (250 to 1500 psi) [1.72 to 10.34 MN/m^2]). For low-pressure service (less than 250 psi [1.72 MN/m^2]) and line sizes up to 17 in. (43.2 cm), the ball valve and the visor valve (half the ball element) should be utilized.

Blade valves (rotating or sliding) should be considered for systems with small lines (nominal 1 in. (2.54 cm)) when the shortest face-to-face dimension is required and system pressures are low.

3.1.2 Leakage Characteristics

Valve leakage shall be a safe margin below the maximum that can be tolerated at the end of the mission duty cycle, minimum leakage being consistent with the state of the art.

The poppet valve should be given the first consideration for low-leakage applications. Leakage rates as low as 0.2 scc/hr GN_2 at 300-psi (2.07 MN/m^2) upstream pressure are possible in small propellant valves. The following advantages can be realized by use of a poppet:

- Either hard or soft seats can be employed to achieve low internal leakage.

- The short-stroke feature allows use of a bellows seal at the poppet stem for zero external leakage.

Butterfly valves may be used where internal leakage rates of 50 to 10 scim (819 to 164 scc/min) helium with 500-psi (3.45 MN/m^2) upstream pressure can be tolerated in 2- to 4-in. (5.1 to 10.2 cm) lines; designs that avoid main-disk dynamic shaft seals and allow the fluid to enter the shaft end cavities may be used. If a zero-leakage hermetic seal is required, use circumferentially welded metal diaphragms that are ruptured by motion of the butterfly disk.

Ball valves with nonmetallic ball seals can achieve leakage rates as low as 3 scim (49 scc/min) helium past the ball with 500-psi (3.45 MN/m^2) upstream pressure; a valve of this type should be considered equal to or better than comparable-size butterfly valves when tight shutoff is required. Employ redundant seals upstream and downstream of the ball element to improve leakage characteristics.

Blade valves are subject to significant seal wear and resultant increased leakage; this type of valve should be avoided for tight-shutoff applications.

3.1.3 Valving Unit Forces

> *Valve motion shall require minimum actuation force consistent with allowable actuator power and size.*

To reduce demands on actuator power and size, when high dynamic flow forces must be balanced, use a balanced poppet valving element for all operating pressures and line sizes. Both the butterfly and ball valving elements are dynamically unbalanced and require increased actuator power and larger actuator envelope. In pump-fed systems where the valve is downstream of the pump, the pressure buildup and decay during the start and shutdown sequences must be evaluated in determining opening and closing torques, because peak system pressure may not occur at the valving element angle that results in maximum dynamic torque. Peak transient surge pressures that occur during shutdown must also be evaluated for valves in both pump-fed and pressure-fed systems.

Blade valving elements are subject to high seal friction forces and should not be used for high pressures. Present operational blade valves, primarily used in gas generators, are subject to nominal pressures of 650 psi (4.48 MN/m^2).

When tight shutoff is not required and flow forces must be balanced to reduce actuator power and size, the rotary or reciprocating sleeve valve is recommended.

3.1.4 Valve Material/Fluid Compatibility

The valve materials shall be compatible with the service, test, and cleaning fluids under static and dynamic flow conditions, impact loads, storage conditions, and the particular load applications.

Use a poppet valve if the reactivity of the fluid limits available nonmetallic materials. The poppet valve provides the following advantages:

- Nonmetallic poppet and seat materials can be contained on four sides, with contact being made on a partially exposed fourth side. This condition prevents cold flow and allows the use of materials that may exhibit slow change in physical properties after propellant exposure.

- Complete metallic design can be achieved on the poppet valving units by using metal-to-metal poppet and seat and metallic bellows at the stem seal.

A butterfly valving unit should not be selected if fluid compatibility appears to limit the choice of nonmetallic material, since no metallic disk seals are presently in operational use, and experience is limited. A matrix listing the materials available and their properties should be developed and used for making the final selection. Materials that lose strength after propellant exposure should be avoided for disk lipseals; such materials compromise seal operation, and excessive valve refurbishment may be necessary. When a soft-seat valve with long-term compatibility is required, a ball valve should be selected. Seal material cold flow and physical property changes can be handled uniquely by capturing the seal on all sides except for the surface contacting the ball. Ball valves with metal-to-metal nonretractable seals have been engine tested (ref. 44); however, no operational ball valves use metal seals, and such seals are not recommended.

3.1.5 Response Characteristics

The valving element shall achieve full-open or full-closed position in the required time, and valving element motion shall not cause excessive impact loads when motion is arrested.

The poppet valving element is capable of employing the shortest stroke to achieve full-open or full-closed position and should be given primary consideration when response time less than 20 msec is a requirement. Damping devices should be incorporated into the power transmission linkage and linear actuators to reduce impact loads on seat material (sec. 3.2.7.4).

The butterfly valving unit is capable of faster response than a comparable ball valving unit because of the smaller mass of the valving element. In both designs, impact loads transmitted into shafts and linkage by the arrest of the valving-element mass after the actuator stops must be considered in determining minimum actuation time, because excessive impact loads can produce severe shaft and linkage damage. Ball valves are not recommended when response times shorter than 100 msec are required.

Blade valves are capable of fast response because of the small angular motion required to achieve full-open position and the small mass of the valving element. However, the blade must maintain contact with the seat ring; otherwise, rapid actuation may result in seat scuffing. See reference 2 for data on blade valve seat design.

3.1.6 Cycle Life

The valve design shall limit impact loads on seat material, minimize sliding or scrubbing action and wear or damage from vibration-induced motion, and be compatible with the service and test fluids over the expected temperature range – all as necessary to achieve required cycle life.

Thoroughly analyze the propulsion system mission requirements to pinpoint critical areas so that the valve will have sufficient life expectancy when exposed to combinations of surge pressure at cutoff, temperatures from heat soakback in valves closely coupled to the injector, vibration modes, and degradation from propellant exposure.

Cycling modes that can cause seat or seal damage, such as rapid dry cycling, should be avoided by taking appropriate precautions in the checkout procedures. An estimate of accumulated time and cycling modes based on realistic conditions should be compiled. The time at various pressure levels and the temperatures that will be reached during checkout must be accurately estimated.

The poppet valving element is recommended when high cycle life (100 000 cycles) is required. Selection of the poppet valve offers the following advantages:

- Little sliding and scrubbing action on poppet and seat sealing surface

- Zero external leakage on the stem seal attainable by use of high-cycle-life bellows

- Low seat-impact loads achievable by incorporation of dashpots

The butterfly, ball, blade, and sleeve valving elements are subject to sliding and scrubbing action in the seating motion; this characteristic limits the life of these designs. However, the lubricity of the service fluid used with a particular combination of valving element and seal materials is an important factor in seal life; therefore, this property should be established. Proper selection of material combinations and use of the lowest seal loads consistent with the allowable leakage can extend the life of these designs to satisfy many requirements. If propulsion system requirements dictate a valve with low pressure drop, small envelope, and extended cycle life, it is recommended that retracting mechanisms for the ball and butterfly valving elements or seats be considered. If this complexity is too much of a penalty, then nonretractable designs with restrictions on checkout cycles, both dry and wet mode, are suitable alternatives.

3.1.7 Contamination Tolerance

The valve shall operate reliably when exposed to normal system contaminants.

When possible, use valving elements that provide a wiping action that tends to rid the sealing surface of contaminants; butterfly and ball valves thus are more tolerant of contamination than the poppet. However, soft nonmetallic seats on the poppet can be designed to encapsulate contaminant particles and improve the tolerance of the poppet. Poppet strokes should be greater than the largest contaminant particle by several orders of magnitude, so that large particles are not trapped between the poppet and seat. To avoid jamming, clearances between reciprocating parts of the poppet that are exposed to the flow system should be several orders of magnitude greater than the largest system contaminant particle. The contamination tolerance of metal-to-metal poppet seats can be improved by providing sufficient hardness and seating force to crush contaminant particles that normally are found in the fluid system or by using a hard-on-soft metal-to-metal closure that allows particles to be imbedded.

3.1.8 Throttling Characteristics

A throttling valve shall possess the required flow-vs-stroke characteristic and positional accuracy and shall require minimum actuation force.

Valving units with a linear flow-vs-stroke characteristic are recommended for applications requiring accurate control at high flow. Equal-percentage flow-vs-stroke characteristics are recommended for applications requiring accurate control at low flow. The other common flow characteristics are recommended only for specialized throttling applications. For a bipropellant throttling valve used for mixture-ratio and thrust control, the linear flow-vs-stroke characteristic is recommended; it provides high-flow-end accuracy and simplifies the mechanical linkage between the oxidizer and fuel valves that is required for mixture-ratio control. To achieve the linear or equal-percentage characteristic, use the poppet or plug-type valving unit. Although other valving unit types can achieve these flow characteristics, expensive contouring of the flow passage is required, whereas the poppet plug and seat shapes are bodies of revolution and are less expensive to fabricate.

The simple flow-passage shapes can also be machined to close tolerances and therefore are recommended for best positional accuracy. Special shaping can be accomplished either in the plug or the seat to achieve the desired flow characteristic. Contouring the outer member, or seat, yields a shorter stroke and more straightforward fluid-flow predictions, as described in section 4 of reference 8 for the noncavitating flow-control valve. For accurate low-flow-end control, bias the plug by skewing the plug guides so that the plug is centered in the seat at the minimum flow position; this practice compensates for eccentricities in the detail ports. Squareness of the plug to the bore has negligible effect on accuracy and may be ignored. At the high-flow end, length tolerances have maximum effect; therefore, provide some overstroke to allow adjustment of the poppet-to-seat position after assembly.

Use a variable-area cavitating venturi valve with a linear flow-vs-stroke characteristic when it is desired to decouple the propellant feed system from downstream pressure disturbances occurring in a combustor or thrust chamber. A summary of the factors involved in obtaining positional accuracy for the variable-area cavitating venturi valves is presented in section 1 of reference 8.

When actuator size and power requirements for a throttling valve are limited, use valving units that can be dynamically balanced; a balanced poppet or plug-type valve is recommended. Methods of pressure balancing are described in section 1 of reference 8.

3.2 MAJOR DESIGN PARAMETERS

The valving unit design and the actuator type shall reflect a thorough analysis of all factors necessary to achieve the required valve function in the control system.

The following analyses and tradeoff studies should be accomplished to ensure that all design parameters critical to the successful functioning of the valve are established:

(1) Accurate pressure-drop calculations substantiated by experimental flow data

(2) Study of system reliability and establishment of valve redundancy requirements

(3) Analyses of flow forces, friction, and actuator force requirements

(4) System analysis of fail-safe mode and establishment of method to achieve the preferred position under failure conditions

(5) Tradeoff studies to establish the actuation system to be used

(6) Selection of the actuator to provide required valve motion

(7) Analysis of timing requirements and method of achieving repeatable valve operation.

3.2.1 Flow-Passage Shape

3.2.1.1 SHUTOFF VALVES

The flow passage of a shutoff valve shall minimize pressure drop and downstream flow disturbance.

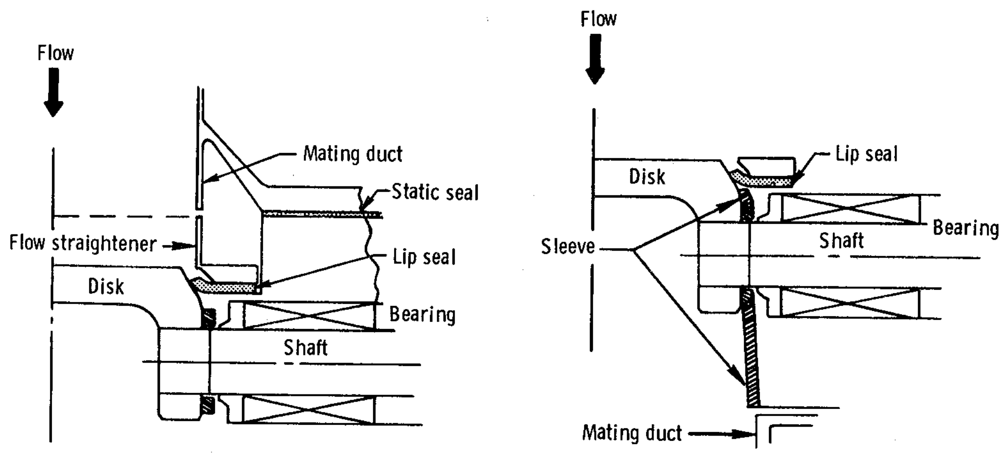
Use simple internal-passage shapes capable of being machined or formed without the use of special contour machining techniques. Use separate orifices for balancing system pressure drops. Procedures for individual valves are described in sections 3.2.1.1.1 through 3.2.1.1.4. Verify calculated pressure drops by conducting flow tests of the valve over the full range of operating conditions.

3.2.1.1.1 Butterfly Valve

The flow passage of a butterfly valve shall minimize changes in flow direction and provide a minimum of flow reduction.

Use flow straighteners or sleeves such as those shown in figure 28 to provide smooth transition from upstream to downstream flow sections and to prevent changes in flow cross-section area.

Use separate idler and drive shafts on a disk of minimum thickness to reduce the projected area of the disk obstructing flow in the full-open position.



(a) Flow straightener. (b) Sleeve.

Figure 28. - Sketches of two methods for reducing flow turbulence in a butterfly valve.

3.2.1.1.2 Ball Valve

The flow passages of a ball valve shall provide unobstructed flow with a minimum of turbulence.

Use full-ported balls to provide a maximum flow area. Use flow straighteners to reduce turbulence in visor valves (fig. 29). Use flow tubes in hollow balls to avoid abrupt changes in flow cross section.

Smooth the flow in ball valves by methods appropriate to the method of loading the seal (fig. 30). Utilize sleeve inserts in bellows used to load ball seals (fig. 30(a)). Shape spring retainers in helical-spring-loaded ball valve seals to reduce exposure of the spring to the flow stream (fig. 30(b)). Utilize Belleville springs for seal loading to achieve a more compact loading arrangement, and shape the spring retainer to minimize turbulence (fig. 30(c)). Employ venturi-shaped sections to reduce ball port sizes to provide smooth transitions and pressure recovery.

Use a 90° contoured ball to route flow and provide a three-way selector valve with low pressure drop.

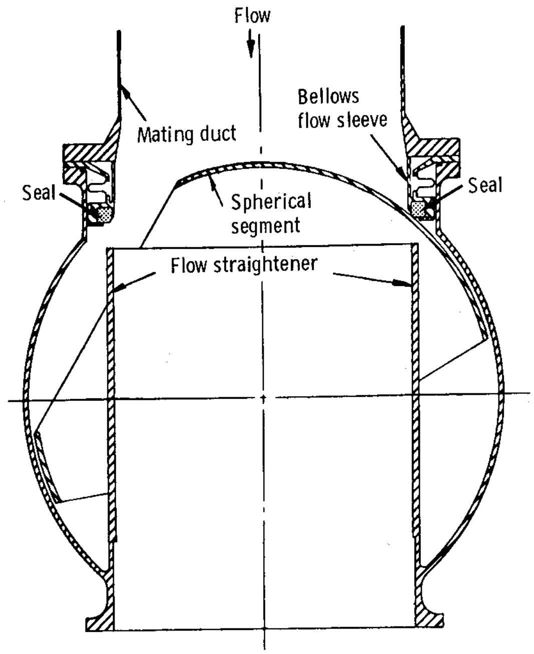


Figure 29. - Cross-section sketch of method for reducing flow turbulence in a visor valve.

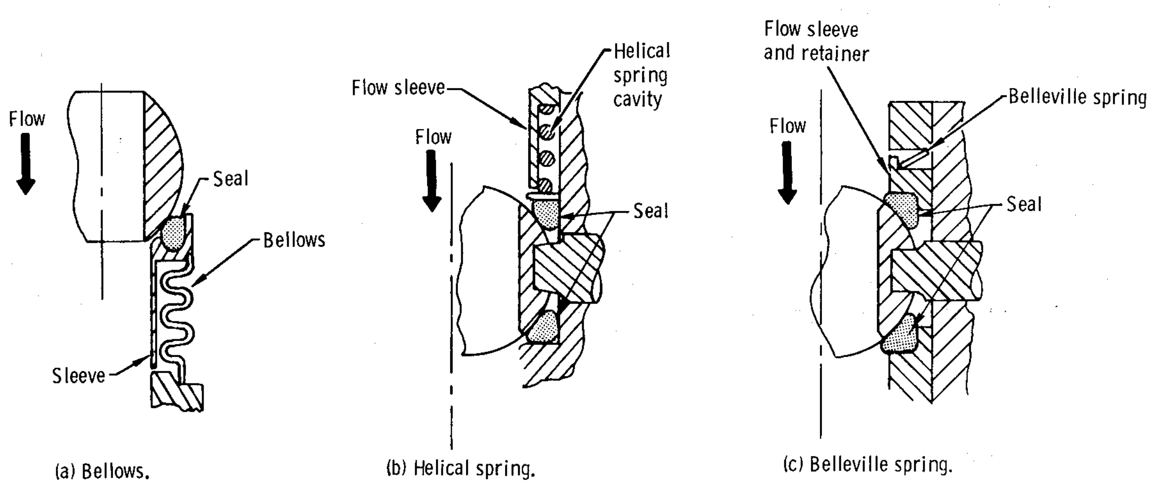


Figure 30. - Cross-section sketches of methods for smoothing flow in ball valves with different kinds of seal loading.

3.2.1.1.3 Poppet Valve

The flow passage of a poppet valve shall provide gradual transition and smooth turns to limit turbulence and pressure drop.

Shape internal flow passages to avoid sudden enlargements or contractions and minimize changes in direction. If changes in flow direction are required in system plumbing (e.g., angle bends or 90° elbows), select globe, "Y", or angle valves that best match the plumbing configuration (e.g., use an angle valve to replace an elbow plus an in-line valve).

To obtain compound curvatures in the flow passages at minimum cost, use castings for valve bodies if possible. Maintain uniform drill-passage flow area in low-flow pneumatic valves. To reduce turbulence, shape or contour the poppet element with either a tail fairing or streamlined nose (ref. 22).

3.2.1.2 THROTTLING VALVES

The flow passage of a throttling valve shall minimize approach and discharge losses and shall provide the preponderant valve pressure drop across the valving unit throat.

For noncavitating throttling valves, provide straight, smooth entry sections to minimize approach losses. Provide a plenum chamber upstream of the throat if an angle entry section is used on a poppet throttle valve.

Use the methods described in reference 8, section 4.2, to establish flow direction and passage design that will provide most of the pressure drop across the valving unit throat. Shape the plug of the poppet by graphical methods presented in reference 45. References 17 and 18 provide design information for utilizing butterfly and ball valves for flow control.

Design cavitating venturi valves to keep head losses to a minimum in each section. Flow sections in a side-inlet cavitating venturi valve are shown in figure 31. The ratio of entry duct area to throat area should be 8:1 or larger. Use a 12° angle entry between the pintle and the cone of the acceleration section. Select diffuser geometry for maximum pressure recovery, using the methods described in reference 8, section 6.3.

3.2.2 Redundancy

If reliability of the system dictates, the valve shall include sufficient redundancy to operate successfully under certain defined failure conditions.

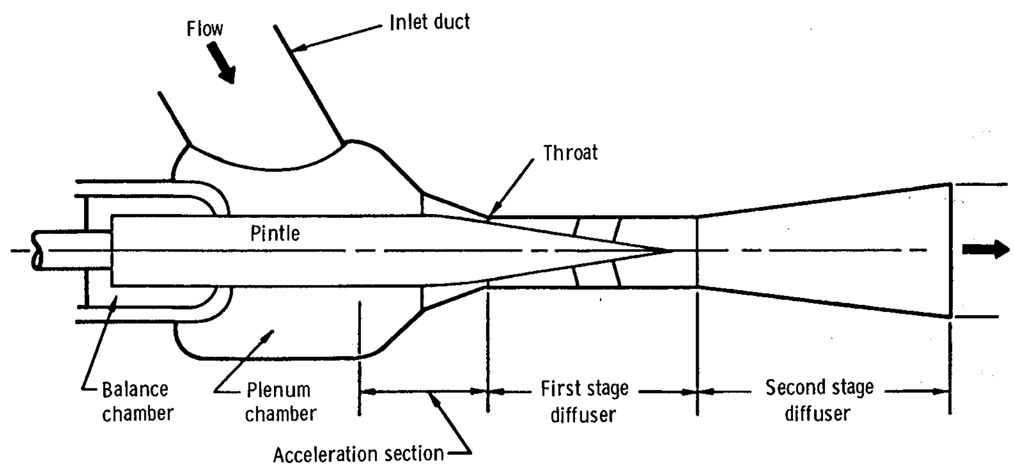


Figure 31. - Sketch showing flow sections in a cavitating venturi valve with an angled side entry.

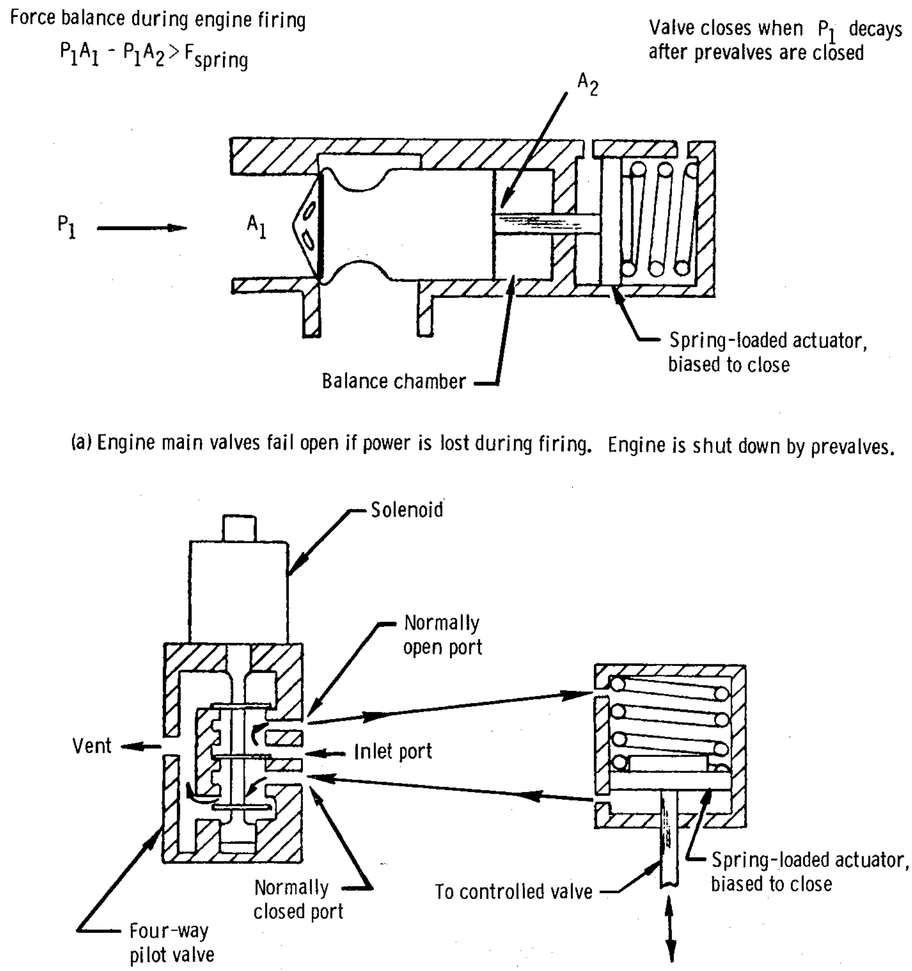
Analyze valve failure modes to establish the redundant design features that are necessary to achieve the reliability specified for the valve assembly. Primary among the failure modes that should be examined are (1) failure of the valve to open or close, and (2) failure of the valve to seal.

If multiple valving elements are required to achieve the specified reliability, select designs with overtravel tolerance that will simplify actuator linkage. Butterfly, ball, or blade valves are recommended when valving elements are ganged, since all these designs exhibit good overtravel tolerance. Poppet valves should be utilized only if the other valve types are unsuitable, since ganged poppet elements require actuation yokes and close control of assembly tolerances to ensure tight shutoff of all joined poppets.

3.2.3 Fail-Safe Mode

The valve shall fail in a safe position when electrical, pneumatic, or hydraulic power is lost.

Establish the fail-safe position early in the design effort so that suitable means for valve biasing can be incorporated in the initial valve design, thereby precluding later redesign of the actuator or valve. Methods recommended for achieving fail-safe positions are shown in figure 32. For control of double-acting cylinders, use a single four-way valve rather than two three-way valves because the fail-safe position of the controlled valve can be ensured. If possible, provide positive movement of the valving element to the fail-safe position by a bias



(a) Engine main valves fail open if power is lost during firing. Engine is shut down by prevalves.

(b) Four-way pilot valve ensures that controlled valve fails closed if electrical power to pilot valve is lost.

Figure 32. - Cross-section sketches of recommended methods for achieving fail-safe modes.

spring. Do not rely on pneumatic or hydraulic actuation power to position the element, because such power may be lost. Utilize dynamic flow forces on the valving element and forces in the balance chamber to assist in reaching the fail-safe position.

3.2.4 Actuator Type

The actuator shall have the motion and force required for valve operation and shall be suitable for use in the valve environment and application.

The design practices recommended below are concerned primarily with valve and actuator mating considerations. System-oriented tradeoffs are treated in reference 46; detailed actuator design is presented in reference 12.

Poppets in RCS valves or in pneumatic or hydraulic control pilots should be electrically actuated with the simplest mechanism with which reliable operation can be achieved. The plunger-type solenoid (fig. 33) is recommended as a simple device that can achieve a 0.125-in. (3.18 mm) stroke and 35-pound (156 N) pull, which is adequate for achieving the

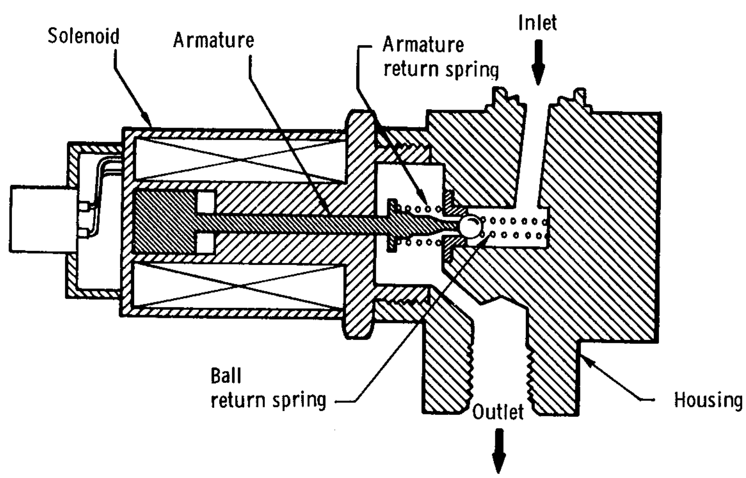


Figure 33. - Cross-section drawing of plunger-type solenoid-actuated valve with spherical poppet.

desired poppet motion and response in small RCS and control system pilots. Selection of the plunger-type solenoid, however, must consider possible jamming by contaminants accumulating in the plunger bore. To eliminate such jamming, use either the torquemotor actuator with the flexure tubes (fig. 34), or the solenoid with flat-face armature and a flexure disk to maintain concentricity of the poppet relative to the seat (fig. 12).

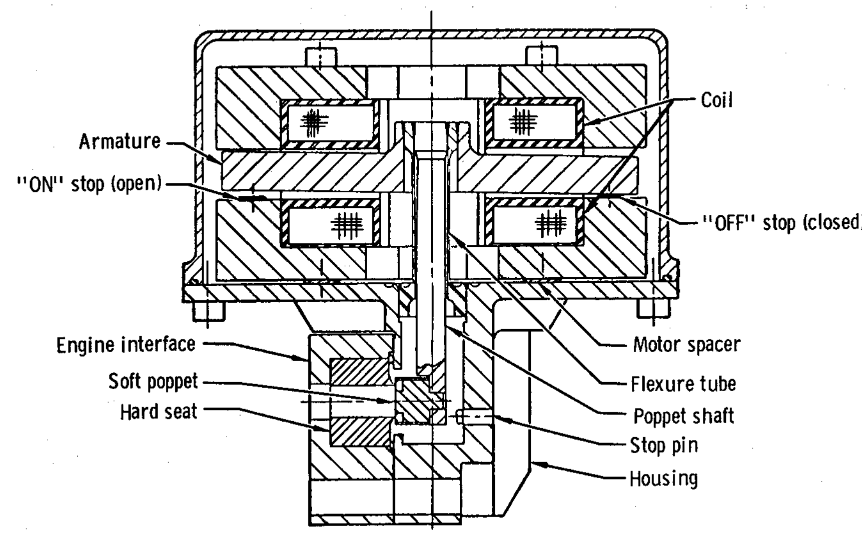


Figure 34. - Cross-section schematic of dc torquemotor poppet valve with no sliding parts (RS-21 bipropellant valve).

For small pressure-actuated poppet valves, use mechanical actuators such as diaphragms or bellows to achieve a compact package that eliminates dynamic seals between the actuator and valve element. Metallic diaphragms usually will not be suitable for small pressure-actuated valves, since high spring rates require pressures higher than those normally associated with engine control systems to achieve the required stroke. Nonmetallic diaphragm materials (e.g., Mylar) are recommended for small pressure-actuated poppet valves (fig. 35). Use bellows for single-acting actuator applications when the pressure is applied externally and a spring return is employed. Diaphragms and bellows actuators are both recommended for low-temperature service conditions, since no dynamic seals are employed in such designs.

In poppet valves where the stroke exceeds 0.100 in. (2.54 mm) and rapid response is required, mechanical actuators such as bellows or pistons that are controlled by electrically operated pilot valves are recommended. Nonmetallic diaphragms are not recommended when stroke exceeds 0.050 in. (1.27 mm), since the diaphragm diameter necessary to achieve the required stroke can increase the hoop stresses to levels that exceed material strengths; in addition, the sensitivity to vibration increases as diaphragm diameter increases.

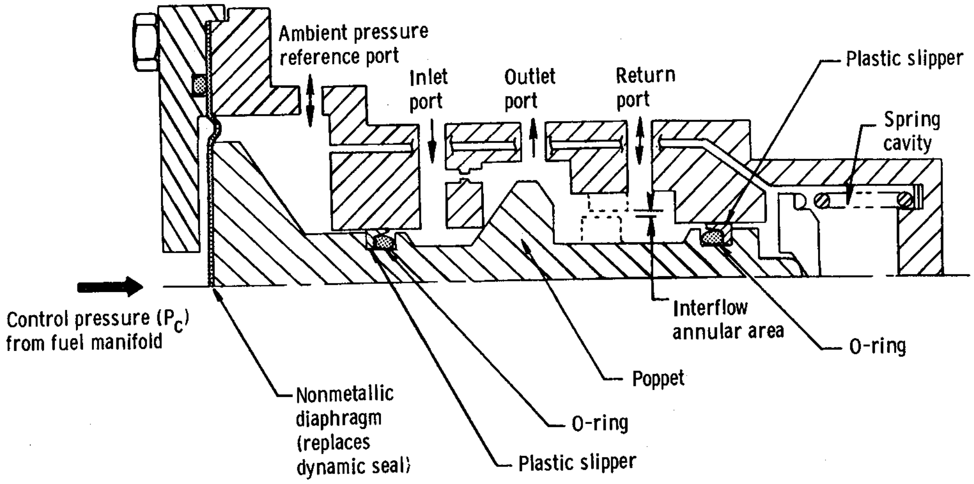


Figure 35. - Cross-section schematic of pressure-actuated poppet valve with nonmetallic diaphragm.

In rotary valves (e.g., ball, butterfly, and blade valves) requiring fast response, use bellows or piston actuators with transmission linkage to convert linear to rotary motion. Consider the reversible dc motor for rotary valves where power requirements are small and slower valve response allows use of geared drive units.

For cryogenic or low-temperature application, avoid piston actuators with O-rings, because heater blankets, warmant recirculation passages, or other suitable heating techniques are required for maintaining proper actuator temperature. Select piston actuators with Mylar or Kel-F lipseals, which will provide excellent sealing to −320°F (77.8 K); bellows actuators are also recommended.

For extended space missions, where actuator leakage cannot be tolerated, diaphragm or bellows actuators are recommended; these types can meet essentially a zero-leakage requirement.

3.2.5 Static Forces

3.2.5.1 SEAL LOADS

The load on the valving element seal shall be sufficient to achieve tight shutoff under conditions of minimum applied force, but shall not generate excessive seat stresses under maximum force conditions.

Establish, from actuation-pressure tolerance and installed-spring or-bellows tolerance, the seal loading variation. Verify that the load for tight shutoff specified in reference 2 for the particular seat type is provided under minimum applied force conditions and that the load does not exceed seating material stresses under maximum actuation pressure and combined maximum spring or bellows preloads.

3.2.5.2 VALVING ELEMENT POSITION

The valving element shall maintain proper position under conditions of minimum actuation force when subjected to the maximum dynamic force.

Conduct a force balance analysis of a poppet valve design to ensure that valving element position can be maintained with minimum actuation pressure and resultant force against the maximum dynamic force and the force from bellows or springs. Butterfly valve designs should be similarly analyzed; however, in the full-open position, the force to hold the valve element position is significantly less than that required to operate the valve and usually is not controlling.

Ball and blade valves can hold full-open position without constant application of force, because dynamic flow forces do not tend to close the valving element in the full-open position. However, the minimum actuation pressure should be reviewed, and the resultant force should be compared with any spring bias forces to ensure that a safe margin exists.

Dynamic forces on spool valves require a thorough analysis because valve porting and shaping will influence valve stability. The method of analysis presented in reference 47 is recommended. Flow tests should be performed to verify the calculations.

3.2.6 Dynamic Forces

3.2.6.1 VALVE OPENING

The actuator opening force shall be sufficient to open the valving element in the required time.

Accurately establish actuator force required to open the valve. Use analytical techniques supplemented by experimental flow data to predict the dynamic forces on the valving element. In the analysis, in pump-fed systems use the longest valve opening time to establish the dynamic force on the valving element, because this force will rise rapidly as pump discharge pressure increases. Use the shortest valve opening time to ensure sufficient force margin to accelerate the valving element and linkage to the necessary speed. The actuator force required to move the valving element should exceed the maximum resistive forces by a factor of at least 1.5.

3.2.6.2 VALVE CLOSING

The actuator closing force shall be sufficient to close the valving element in the required time and provide tight shutoff.

Accurately establish actuator force requirements to close the valve and verify them by test. With propellant-actuated valves, accurate estimates of closing-force requirements are necessary, since decaying pump discharge pressure will reduce any safety factor if closing is delayed. Closing friction increases sharply in the last 15° of butterfly disk motion as the disk engages the lip seal. Tests are required to ensure that actuator force is adequate to achieve positive sealing. To provide a safe margin, the actuator closing force should exceed the maximum resistive forces by a factor of at least 1.5.

3.2.7 Valve Response

3.2.7.1 ELECTRICALLY ACTUATED VALVES

The electrical actuation device shall supply sufficient force in adequate time to achieve the required valve response time.

Whether the actuator is an electric motor for direct drive of rotary motion valves (ball, butterfly, blade, or sleeve) or a solenoid or dc torquemotor for actuating poppet type valves, the actuation force or torque must be sufficient to overcome friction, closing forces exerted by bias springs and fluid pressure, and inertia of moving parts. To ensure achieving required response time, the accumulated tolerances in effective sealing area and pressure, solenoid-to-armature air gap, solenoid coil resistance, and solenoid attractive force – thermal effects in each instance being taken into account – must be developed for a worst-case condition.

A dc torquemotor actuator is recommended for valves in which electrical delay must be minimized to achieve satisfactory response. If the longer electrical delay of a solenoid does not present problems in achieving the required response, a solenoid should be used for design simplicity. To achieve faster response in electrically actuated valves, use special driving circuits to shape the peak driving voltage.

3.2.7.2 PNEUMATICALLY AND HYDRAULICALLY ACTUATED VALVES

The pneumatic or hydraulic actuation system shall supply adequate fluid flow and pressure to the actuator to achieve required travel time and provide forces equal to or greater than resistive forces.

Size fluid actuation systems by determining system pressure drops at flowrates required for the actuator stroke to achieve the required valve travel time, and use final pressure at the actuator to ensure that the force is equal to or greater than the resistive force. Analyze maximum actuation times required in pump-fed systems to ensure that the valve can open against increasing dynamic pressures on the valving element from rising pump discharge pressure. Review maximum closing times in propellant-actuated valves to ensure that sufficient closing force can be developed with decaying pump pressure to provide positive shutoff.

3.2.7.3 FRICTION

The valve assembly shall provide positive design features to prevent friction from affecting response.

When stroke allows, use a flexure-mounted poppet to avoid the jamming and galling problems associated with contamination of sliding surface guides. Use flexure-mounted flat-face armatures for wet-mode operation in small RCS propellant valves instead of plunger-type armatures that are subject to contamination jamming at close clearances. When plunger-type solenoids are utilized, provide diametral clearances several orders of magnitude greater than the largest contaminant size expected. For dry-mode operation of small poppet valves for RCS engines, use flexure-mounted poppets together with the dc torquemotor to avoid friction problems from guides. On larger valves subjected to thermal extremes (either cryogenic or elevated temperatures), provide adequate clearances and a safe margin of actuator force so that the valve can operate satisfactorily even when there is some increase in friction.

On ball and blade valves, limit rubbing velocities on seals to less than 6 ft/sec (1.8 m/sec), since heat generated by seal friction can damage seals in these valves (ref. 48).

3.2.7.4 INERTIA OF MOVING PARTS

The valve assembly shall withstand the impact loads associated with the minimum required valve travel times.

In rapid-response valves, provide stops on the actuator to decouple actuator mass; use dashpots to reduce impact forces on poppet valve elements if the actuator remains coupled. Evaluate the large moment of inertia of the ball or butterfly disk, and verify that at the minimum valve travel time the stresses in the shaft and linkage that result from stopping the rotation of the ball or disk do not exceed allowable stresses for the material. Use hollow-ball, hollow-shaft designs to reduce inertia and to allow energy to be absorbed more uniformly along the length of the shaft.

3.2.7.5 LENGTH OF STROKE

The stroke of the valve shall be consistent with the required response time.

Use minimum-stroke designs where fast valve response is required. In poppet valves, consider increased poppet diameter to achieve required flow with short strokes. For rotary valve actuators, accomplish tradeoffs between short-moment-arm actuators (e.g., eccentrics or small rack-and-pinion drives) and more conventional lever-and-link designs. Select the actuator linkage that can produce the required valve travel time and utilize the largest moment arm consistent with the envelope restrictions, so that bearing loads are kept low.

3.2.7.6 TIMING REPEATABILITY

The valve opening and closing times shall be repeatable from valve to valve and from actuation to actuation within the limits established by control-system requirements.

To achieve repeatable valve timing, the actuation force to open or close the valve must exceed resistive forces by a factor of at least 1.5. Combined friction forces should not exceed 10 percent of the resistive forces the actuator must overcome.

Changes in friction in a valve that result from temperature changes altering clearances or from O-ring swell, contamination, lubricant dryout or loss, wear, or corrosion should be minimized as follows:

(1) Analyze thermal growth or contraction and ensure that adequate clearances are maintained.

(2) Select compatible nonmetallic materials that are dimensionally stable after exposure to propellant.

(3) Filter service, actuation, and test fluids before they enter the valve.

(4) Select compatible lubricants

(5) Select material combinations that are not subject to galling and are compatible with the service, actuation, and test fluids.

A hydraulic or pneumatic valve actuator may be orificed to affect the force-vs-time relationship; however, the effects of temperature variations in the actuator and actuating fluid must be controlled by orifices and thermal compensators described in reference 12.

In redundant valve designs, such as the series-parallel valve assemblies, use fast and slow sets of valving elements. Allow the slow set to provide timing for the engine sequence.

In bipropellant valves, achieve relative timing between fuel and oxidizer valving elements by design of the mechanical linkage from the common actuator. For poppet valves, use an adjustable yoke. For rotary valves, vary the crank geometry or index one valving element relative to the other so that a repeatable time interval between release of oxidizer and fuel is achieved.

3.3 DESIGN INTEGRATION OF VALVE SUBASSEMBLIES

3.3.1 Integration of Actuator and Valve

The integration of the actuator and valve shall

- *Result in minimum envelope*
- *Separate fuel and oxidizer as required*
- *Provide adequate thermal barriers*
- *Ensure structural integrity*
- *Provide flexibility for uprating.*

Use vented or purged cavities for valve assembly designs when a hydraulic actuator is buried within an oxidizer valve (fig. 10). On bipropellant valves, where the oxidizer and fuel valving elements are actuated by a common shaft, use separated housings, if possible, to avoid creating common cavities; if common cavities cannot be avoided, use large cavity volumes and vent passages so that any leakage is rapidly diffused (fig. 11). Use wet-mode operation in small solenoid valving units to eliminate dynamic stem seals or bellows. Isolate dc torquemotor actuators from the propellant stream by flexure tubes of all-welded construction.

Use bolted assemblies between the valving unit and the actuator on poppet valves for ease of maintenance. Use all-welded construction for lightweight and positive sealing, but recognize that time for valve servicing will be increased.

On butterfly and ball valving units, use integral designs for valving unit and actuator to provide the lowest weight and smallest valve assembly envelope. Provide a capability for uprating the actuator by providing additional housing thickness for the actuator cylinder. Use lip seals of Mylar or Kel-F to provide low-temperature sealing in the actuator of cryogenic valves with integral housings for valving unit and actuator. Avoid O-ring dynamic seals for actuators of cryogenic valves, since thermal barriers will be required and heater blankets and warmant passages must be used.

To provide maximum flexibility for later uprating of butterfly and ball valving units, if weight and space permit, use a separate valving unit housing bolted to the actuator housing.

Keep the valve envelope compact and avoid actuator overhangs to avoid amplification of vibration. If possible, place the actuator axis 90° from the flow axis on the butterfly valve, so that structural webs can be created to enable the integral assembly to withstand vibration and yet be lightweight.

3.3.2 Transmission Devices

Transmission devices for converting linear motion to rotary motion required for valve operation shall occupy minimum space, have adequate allowance for impact loads, exhibit minimum backlash, and not be subject to galling.

Use the crank-and-link design for all rapid-response valves that operate in less than 100 msec. An integral crank-and-drive shaft is preferred; it eliminates problems of alignment and adjustment. Use a square-end rather than a spline drive if a separate crank and shaft are employed.

Design the linkage to withstand the full actuator force that would be transmitted to the crank and link if the ball or disk seizes. Fabricate the crank and linkage of a ductile material such as 431 steel or Inconel 718. Fabricate the pin or fastener of a hardened material such as 440C steel heat treated to Rockwell C 53 to 58. Use an 8-μ in. (0.20 μm) finish on the pin and 32-μ in. (0.81 μm) finish on the mating hole. Apply a dry-film lubricant to the pin as recommended in section 3.4.1. Use pin retention shown in figure 36 to avoid lock washers; this method restricts the free motion available to the pin by a low-friction bumper that rides on the linkage cavity plate.

The rack and pinion is a good way to achieve a compact envelope, but restrict its use to smaller valves; backlash may be troublesome as valve size increases. For fabricating a rack and pinion, a material such as beryllium copper is preferred over Inconel 718 because machining can be accomplished before the material is heat treated to the full-hard condition. To improve wearing qualities, beryllium copper used in cryogenic service for both

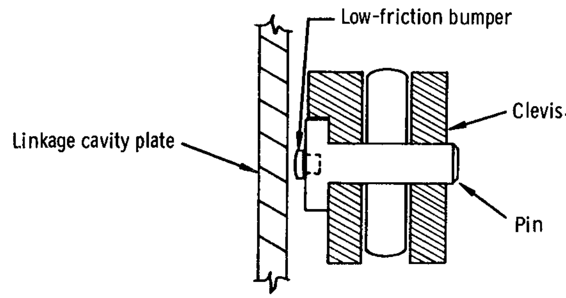


Figure 36. - Recommended method for pin retention in a crank-and-link design.

the rack and the pinion material should have a chromium plate on the pinion and a flashed silver plate on the rack. Use a 32-μ in. (0.81 μm) finish on the tooth face and a 63-μ in. (1.60 μm) finish in the root.

3.3.3 Transmission Shafts and Bearings

The valving element and transmission shaft bearings shall be the minimum size that will withstand the radial and axial loads and maintain alignment.

Use journal or needle bearings to reduce bore diameters in the valve housing required to accommodate bearings. Pick up axial loads on butterfly valves by use of crosspins (fig. 14). Use double integral shafts on ball valves to reduce axial loads (fig. 15). When both radial and axial loads must be handled, eliminate the need for a separate thrust bearing by using ball bearings.

If sufficient corrosion resistance in the bearing can be obtained, eliminate dynamic shaft seals and allow the actuating fluid to enter the linkage cavity; use static seals to prevent external leakage.

When bearing materials may be subject to corrosion, use shaft seals to prevent exposure of rolling-element bearings to the fluid stream. Provide a barrier to prevent the entry of moisture, and use vent port check valves to vent sealed bearing cavities.

Avoid use of materials subject to stress corrosion in highly stressed parts that are subject to corrosion by the atmosphere or by a leaking corrosive propellant.

3.3.4 Thermal Expansion/Contraction, Distortion, and Loads

The valve assembly shall operate reliably in the specified thermal environment.

Analyze dimensional changes due to thermal expansion or contraction of detail parts of the assembly. Ensure that proper alignment and adequate clearances are maintained over the entire temperature envelope, even when the valve is subject to thermal shock. Select materials for their dimensional stability and use special stabilization processes during fabrication of valve components to avoid permanent dimensional changes that can occur later during thermal cycling. For cryogenic applications, 440C CRES must be stabilized to prevent phase changes of the material during low-temperature cycling. Large aluminum-alloy housings may require cryogenic stabilization before final machining operations to avoid later permanent distortion causing severe misalignments.

Select materials that compensate for thermal gradients; e.g., stainless steel butterfly disks may be used with aluminum valve bodies to avoid excessive leakage during chilldown. Minimize thermal transient problems by special design techniques; e.g., avoid very thin sections. Reference 2 contains detailed recommendations for these design techniques; reference 49 discusses dimensional instability in metals, its causes and effects, and methods to control stability.

3.3.5 Imposed Loads at Interface Mounting Points

The valve assembly shall withstand loads imposed at interface mounting points.

Conduct stress analyses to ensure acceptable deflection and distortion and to avoid compromising valve operation by body distortions when the valve assembly is used as part of the load-carrying structure. Die forgings are recommended for valve housings that must carry engine structural loads, i.e., when hard, load-carrying lines are used to support various engine subassemblies or when severe interval-load conditions exist. A cast body housing may be used if the valve assembly interfaces with flexible lines, because the interface loads are lower.

3.3.6 Environmental Factors

3.3.6.1 MOISTURE

The valve assembly shall provide for positive exclusion of moisture.

Provide vent port check valves to exclude moisture-laden air from valve cavities exposed to low-temperature thermal cycling. Use protective covers or suitably routed discharge lines on the exit of vent valves or propellant duct bleed valves to prevent entry of moisture. Figure 20 shows a suitable cover.

3.3.6.2 VACUUM

The valve assemblies for space applications shall function reliably in space vacuum.

Determine the effects of sublimation on nonmetallic seals during prolonged exposure to vacuum. Select a suitable seal material for the most adverse conditions. A list of seal materials is provided in section 13.6 of reference 4.

On metal-to-metal closures, the possibility of cold welding between sealing surfaces of a propellant valve should be analyzed. Design information derived from cold-welding experiments with valves in space applications is presented in references 37 and 38.

Analyze the potential clogging of downstream plumbing by evaporatively frozen propellant that leaked past the valve element seal, and take design precautions in the valve assembly or system to ensure that clogging will not occur. Heater blankets may be used to avoid evaporative freezing, but other methods that utilize the heat available from the propellant or other mass are preferred, because heaters require expenditure of vehicle electrical power. Reference 50 provides an example of a solution requiring no additional power input to prevent freezing.

3.3.6.3 ACCELERATION, SHOCK, AND VIBRATION

The valve assembly shall withstand the effects of acceleration, shock, and random and cyclic vibration.

Maintain high seal loads and keep valving element mass small to prevent scuffing of poppet valve seats in the closed position. Decouple the actuator from the poppet to decrease moving mass.

Use off-center butterfly disk designs, so that the disk can rotate clear of the disk lip seals and thereby prevent wear of the seals during vibration of the valve in the open position.

Attach the valve assembly to the vehicle structure or engine to minimize amplification of force levels during vibration. To ensure integrity of the valve assembly, conduct a severe, but representative in all respects, vibration test program based on a specified vibration level. Provide sufficient structural strength to enable the valve assembly to withstand cyclic vibration modes produced by combustion instability that may occur during development of a new engine system.

Keep bearing clearances to a minimum to avoid fretting. Attach internal parts such as flow shrouds firmly to avoid vibration-induced damage. Maintain a compact envelope for actuator and valve, so that vibration force levels are not amplified.

3.3.6.4 RADIATION

The valving unit shall operate reliably in the expected radiation environment.

For nonmetallic static and dynamic seals, select materials that are resistant to damage caused by the type of radiation the valve will be exposed to on the planned mission; section 13.6.3.7 of reference 4 provides guidance in selecting materials for the radiation environment. Analyze the effect of shielding provided by metallic portions of the valve and utilize the shielding that can be obtained to reduce the exposure of any critical components. If lubricants are required, select materials that will be stable in the radiation environment. Reference 4 noted above also provides guidance for selection of lubricants.

3.3.6.5 ZERO GRAVITY

The valving unit shall operate reliably and perform the required function in the zero-gravity environment.

All required forces must be applied by positive devices such as springs and flexures, pneumatic or liquid pressure acting on pistons, diaphragms or bellows, and electrical devices; no reliance can be placed on weights.

Special valving unit designs or propellant settling systems (ref. 51) must be used so that liquid is not lost during tank venting operations.

Heat must be dissipated without convective heat transfer in the zero-gravity environment; use conductive paths to available heat sinks in the vicinity of the valve to dissipate heat energy. Brackets of sufficient cross-sectional area can be used. The length of the conductive heat path should be as short as possible.

3.3.6.6 DORMANCY

The valve assembly shall perform its intended function after periods of dormancy.

Ensure that the exposure of the valve assembly to the space environment and to the local spacecraft environment will not cause changes in material properties and dimensions that will affect valve operation.

If valve timing is critical, utilize actuator and valving unit seals that do not require increased starting force after long periods of dormancy. Lip seals are preferred over O-rings for minimizing changes in starting friction that may result from long inoperative periods.

3.3.7 Valve Latching

Latches to hold valving element position without power shall not affect reliability.

Latching mechanisms should be designed with controls such that the valve cannot be operated until the latch is fully disengaged. On smaller valve assemblies, provide actuator force margin adequate to disengage the valving element from detents or magnetic latches employed.

Latches required for test but not for flight operations should be designed so that they can be removed readily after static testing is complete.

3.3.8 Filtering

The valve assembly shall have sufficient filtration to ensure reliable operation if the assembly is not tolerant of system contaminants.

For booster-engine propellant valves, which do not require restart, filter propellant only during tanking; weight and pressure-drop penalties of feed-line filters make their use impractical in flight.

When prolonged coast periods and restart are required, use filters upstream of valves to ensure that close tolerance fits are not jammed and that seating materials are not damaged by contaminants in propellant feed systems. Install filters integral with the valve housing to reduce built-in contamination and give maximum protection.

Use filters downstream of explosive-actuated valves to catch debris and prevent it from reaching critical downstream components.

In pneumatic or hydraulic control valves provide upstream filtration to exclude contaminant particles that could jam critical clearances or clog timing orifices.

Detailed design information for filters is presented in reference 41.

3.3.9 Purging, Draining, and Flushing

The valve assembly shall admit of thorough purging, draining, and flushing after exposure to propellant or test fluid.

Provide ports for flushing residual propellants from the valve assembly after valve exposure to toxic or corrosive propellants.

If possible water contamination requires pretest draining, provide low point drains on the valve assembly as it is oriented in the engine system.

Incorporate purge ports downstream of the valving unit if system purges at start or shutdown are required to clear lines of residual propellants.

Locate drain ports so that entire valve cavity is drained with the valve in the various positions that would be experienced during operation.

Use quick disconnects or flared tube unions to avoid possible accidental stripping of threads in the valve housing.

3.3.10 Instrumentation

Instrumentation on the valve assembly shall not reduce reliability of the valve, produce adverse interaction between functional and monitoring instruments, or cause electromagnetic interference.

Use dual systems for functional and monitoring classes of instrumentation, so that a malfunction in monitoring instrumentation cannot disrupt functional instrumentation needed for performance of the mission.

Provide fail-safe design features to prevent failure of an instrumentation subsystem resulting in a malfunction of the valve.

3.3.10.1 INTERNAL PRESSURE

The instrumentation for measuring valve internal pressure shall provide accurate and reproducible data.

Monitor the valve internal pressure as directly as possible; avoid unnecessary pressure taps on flight hardware.

Mount pressure transducers such that sensing lines are short, connectors are limited in number, and lines are self draining. If pressure taps are not required for flight instrumentation, then the valve should be designed to permit inclusion of the taps on valves selected for development testing.

3.3.10.2 VALVING ELEMENT POSITION

Valving element position-indicating devices shall be sufficiently accurate to satisfy monitoring or functional instrumentation requirements, shall have adequate overtravel tolerance, and shall be capable of operating in the vibration environment.

Avoid short-stroke microswitch assemblies for position indication, since the lack of overtravel makes switch assembly adjustments critical.

Use a rotary resistor such as that shown in figure 24 to provide good overtravel characteristics at the open and closed positions and a valve position trace for intermediate position indication. Hermetically seal the switches to avoid moisture problems. Mount the switches on the valve assembly to avoid amplification of vibration force levels, since wiper and resistor elements in these switches are sensitive to vibration.

A variable-reluctance position indicator is recommended for closed-loop servo systems, because this unit provides an accurate position trace; however, weight, complexity, and possible signal interference must be considered. Mount the indicator switch close to the valving element to avoid erroneous indication if transmission shafts or linkage fail.

3.3.10.3 TEMPERATURE

Thermocouples for monitoring valve temperatures shall have compatible probes, positive sealing, and response characteristics suitable for the application.

If the thermocouple penetrates the cavity, it must be compatible with the service or test fluid. Place thermocouples in intimate contact with the particular areas of the valve where thermal-effect information is desired. Avoid designs that interfere with obtaining required transient data. Thermal test procedures should specify the exact locations on the valve where thermocouples should be mounted and, if possible, the method of mounting.

3.3.10.4 ACCELERATION

Valve external surfaces shall admit of accelerometer attachment by simple means.

Provide surface configurations suitable for simple mounting of accelerometers with epoxy resin. If this is not possible, special valving units having drilled and tapped holes at locations where maximum vibration amplitudes are expected must be provided for vibration testing.

3.3.10.5 STRAIN

Strain measurement methods shall be consistent with the test pressures or forces involved.

Although simple dial indications can be used for some strain test setups, for tests under high pressure, remote indicating strain gauge instrumentation is recommended.

3.3.11 Valve Sterilization

The valve assembly shall withstand sterilization of the system without compromise of valve performance.

Select materials for valve seals that are not affected by the combinations of temperatures and sterilizing fluids to which the valve will be exposed. With metallic materials, consider increased corrosion rates that may occur. Ensure that the high temperature will not cause binding of parts of the valve assembly because of thermal expansion of parts. Evaluate the actuator design to ensure that the solenoid windings or explosive charges will not deteriorate and thereby alter valve performance.

3.3.12 Tolerance Stackup

Valve component and assembly tolerances shall not result in interferences or excessive clearances.

Perform a stackup of dimensions and tolerances of components of the valve assembly prior to release of detail parts for fabrication. A valve layout 10X scale should be made to show the extreme stackup of tolerances of angular, linear, and concentric dimensions, so that interferences as well as excessive clearances can be recognized and corrected. The stackup review should be considered a formal effort separate from the design. As part of this formal review, the drawings should be coordinated with the shop personnel to ensure the fabricability of the detail parts of the valve.

3.3.13 Preventing Misinstallation

Provisions for integration of valve assembly components and mating subassemblies shall prevent misinstallation.

During assembly of valves with critical clearances, use 10X magnification to examine all parts prior to their installation; eliminate burrs that may break off and jam close-tolerance fits. Figure 25 shows examples of burr types and gives inspection guidance.

Use protective closures on the assembled valve to prevent entry of contaminants, protect sealing surfaces, and prevent damage to externally threaded ports. Use a consistent color code to signify nonflight hardware, and document and control all closure designs to deter the use of unauthorized closures. Make the closure readily visible by making it at least 0.125 in. (3.18 mm) thick. Use a hat-shape cross section to increase the thickness of the closure. Make the closure plates for flanges larger than the flange to facilitate ease of detection. The bolt-hole pattern should have only 1/2 of the flange holes to prevent inadvertent installation of the closure plate during installation of the valve into the next higher assembly. Holes in the gaskets should be oversize to prevent chafing with fasteners. Use closure fasteners that are nonstructural, if possible, or too short to be used in the assembled flange, so that nonflight hardware cannot be used accidentally.

Use nylon packaging materials for contamination-sensitive valves.

3.4.3 Purging and Flushing

The valve assembly shall not experience prolonged exposure to residuals of potentially corrosive fluids.

Flushing procedures should be established for valves in service with corrosive fluids. Valve assemblies exposed to N_2O_4 should be flushed with trichlorotrifluoroethane to prevent residuals from corroding or seriously degrading valve internal surfaces. Isopropyl alcohol is recommended as the flushing medium for hydrazine and its derivatives. Do not use isopropyl alcohol, however, for flushing valve assemblies exposed to MMH, because sludge that can cause the valve to stick will be formed.

Do not use water as a flushing medium for valve assemblies, because incomplete removal of water can lead to corrosion of internal parts.

Do not use phosphoric acid flushes unless long-term material compatibility can be established, since small amounts of corrosive solution may remain trapped in the valve passages.

In storable-propellant engine systems, shutdown-sequence purge should be employed to remove residuals from the lines after shutdown; this purge will minimize buildup of crystalline deposits that result from reaction of nitrogen tetroxide and hydrazine and its derivatives with engine materials after the engine burn. These ammonium-nitrate deposits can damage nonmetallic seals and result in leakage past the valving element.

3.4.4 Qualification Testing

Qualification testing shall provide substantial proof that the valve assembly will meet flight requirements.

Specify a rigorous component qualification program, realistic but sufficiently severe to ensure integrity of the valve design. Expose the valve to temperature extremes, proof-pressure tests, and leakage tests, and subject it to environmental conditions such as moisture, dust, salt spray, vacuum, acceleration, and random and cyclic vibration. Often combinations of two or more of these tests are required and specified. Recommended environmental test methods are given in reference 53. Section 15 of reference 4 provides information useful in establishing a component qualification test program.

3.5 ENGINE, STAGE, AND SPACECRAFT CHECKOUT

The valve assembly shall not be exposed to checkout conditions that exceed the projected cycle life or other design specifications.

Monitor the checkout operations and review the procedures to ensure that the valve assembly is not exposed to excessive pressure, high temperatures from rapid pressurization, propellant transfer-line pressure surges, extended energization of solenoid actuators, excessive valve actuation, or rapid valve cycling. Review these operations to ensure that existing valve requirements remain valid. If checkout procedures result in a gross deviation from the valve design requirement (e.g., excessive valve actuation), either change the procedures or revise the requirements to ensure that sufficient cycle life remains for the valve to complete the intended mission.

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GLOSSARY

Term or Symbol	Definition
a, b	constants in flowrate equation
actuator	device that converts control energy into mechanical motion to operate a valving element
actuation time	elapsed time from receipt of signal to valve first motion
ambient temperature	temperature of the environment surrounding a valve
backlash	dead space or unwanted movement that results from fabrication and assembly tolerances in linkages; excessive backlash produces poor positional control of the valving element or errors in position instrumentation
balance chamber or piston	chamber used to balance the pressure forces exerted on a poppet valving element and thereby decrease the force necessary to actuate the element
ball valve	rotary-action valve using a ball with a flow passage that rotates to align the mating upstream and downstream lines
Belleville spring	truncated, conical, metal spring washer that can provide a negative mechanical spring rate
bias spring	spring installed in a valve actuator to obtain a preferred position when power is removed
bipropellant valve	valve incorporating both fuel and oxidizer valving units driven by a common actuator
blade valve (rotary)	valve utilizing a plate that is rotated transversely in a slotted chamber between upstream and downstream lines
blade valve (slide)	valve utilizing a flat plate that slides transversely in a slotted chamber between upstream and downstream lines
burst test	pressure test of the valve housing to determine whether the housing can withstand the calculated burst pressure
butterfly valve	valve constructed to close off or throttle flow by rotating a circular disk around a transverse axis within the flow passage

Term or Symbol	Definition
cavitation	formation of bubbles in a flowing liquid when the static pressure becomes less than the fluid vapor pressure
C_D	discharge coefficient (valve)
C_V	flow coefficient
cavitating venture	poppet-type valve that utilizes a pintle to vary throat flow area; because of cavitation effects, flow of the liquid remains constant for any set throat area even though the downstream pressure varies
contamination tolerance	the ability of a valving unit to operate in a fluid system without contamination-produced failure even when a specified level of contamination is present
cryogenic	fluids or conditions at low temperatures, usually at or below −150° C (123 K)
cryopumping	the condensing and freezing of water vapor and gases on extremely cold surfaces (near liquid-hydrogen temperature) with the result that, in a confined cavity, the pressure is lowered
cycle life	number of times a valving unit may be opened and closed and still possess sufficiently low internal leakage to meet specified leakage rate
cyclic vibration	vibration mode, induced by rough combustion in a rocket engine, that produces severe g loads on a periodic basis at one predominant frequency
cylindrical slide or piston valve	valve constructed with a cylindrical bore with annular holes that are covered or uncovered by sliding of a piston through the bore; used primarily as a sequence valve
decontamination	cleaning process to ensure that residual corrosive fluids remaining in the valve assembly after test are flushed out or neutralized to avoid damage to metallic and nonmetallic materials
disk	valving element of a butterfly valve
dry cycle	functional testing of the valve without propellant or test fluid in the flow passages
dynamic seal	mechanical device used to minimize leakage of a fluid from the flow-stream region of a valving unit when there is relative motion between the sealing interfaces

Term or Symbol	Definition
earth-storable propellant	propellant with a vapor pressure low enough that it can be stored on earth as a liquid in a moderate-pressure container
elastomer	polymeric material that at room temperature can be stretched to approximately twice its original length and on release return immediately to its original length
electrical delay	time period from the initial electrical signal to valve first motion
equal percentage characteristic	relationship between valve flow and the valving element stroke in which a percentage of change in opening at any stroke increment will cause an equal percentage change in flow
evaporative freezing	freezing that can occur when a liquid leaks into hard vacuum and expands to pressures below the triple point of the liquid
fail-safe	philosophy in the design of propulsion system valves and associated hardware that seeks to avoid the compounding of failures and allow the greatest chance for safe termination of the mission; fail-safe design provisions ensure that the valve will move to a predetermined "SAFE" position if power is lost
flat-face armature	solenoid actuator utilizing a flat armature that is flexure mounted to avoid sliding fits in the valve assembly
flexure disk	supporting member that allows poppet axial motion but restrains rotation and prevents misalignment of concentric fits
flexure tube	interconnecting member between the valving element and a dc torquemotor that transmits motion and seals the flow stream; the tube is rigidly attached to the valve body at one end and acts as a spring
flow tube	tube inserted in hollow ball of a ball valve to smooth the flow and to reduce turbulence and pressure drop
flow-to-close valve	valve in which the flow direction and forces acting on the valving element provide a closing force; in a poppet valve this direction is termed "flow over the plug"
flow-to-open valve	valve in which the flow direction and forces acting on the valving element provide an opening force; in a poppet valve this direction is termed "flow under the plug"
four-way valve	valve having four controlled working passages such that there are two simultaneous flow paths through the valve; commonly used to control double-acting actuators

Term or Symbol	Definition
fretting	mechanism of wear that acts on mating metallic materials to produce surface damage when one surface moves relative to the other; vibration and cryogenic temperatures are aggravating factors
GG	gas generator
g	acceleration due to gravity
galling	progressive surface damage of mating surfaces resulting in increased friction and possible seizure
H_{loss}	reduction in static head
heater blanket	electrical heater employed on a cryogenic valve to prevent actuator temperature from falling below stated operating minimum
hot gas	combustion products or gaseous discharge from a heat exchanger; hot-gas temperature can reach 1300° F (978 K), depending on the process, in state-of-the-art propulsion systems
HS	head suppression
hydraulic	operated, moved, or effected by liquid used to transmit energy
hydraulic dashpot	device used to reduce the velocity of the actuator as it approaches a fixed stop, so that impact energy levels are reduced
journal bearing	sliding-surface bearing that uses combinations of metals or nonmetallics to achieve low friction, compatibility, and wear resistance
K	resistance coefficient, $K = \frac{H_{loss}}{v^2/2g}$
laminar-flow bench	bench used for valve assembly operations; the bench is closed at the sides and top and has a rear wall that distributes filtered low-velocity air across the work area to prevent entry of airborne contaminants
latch	mechanical or magnetic device that maintains a valve in either the open or closed position without the constant application of power
lever-link	mechanical linkage between the actuator and the valving element of a rotary valve that consists of a lever or crank on the rotary member and a link with clevis connections from the lever to the actuator shaft
L/D	length-to-diameter ratio

Term or Symbol	Definition
linear characteristic	straight-line relationship between valve flow and valving element stroke at a constant value of pressure drop
main valve	valve located just upstream of the thrust chamber injector
metal-to-metal seal	an internal seal in a poppet-type valve that is achieved with hard-on-hard or hard-on-soft metallic seats
MFV	main fuel valve
mission duty cycle	total propulsion system requirement for a scheduled number of valve operations for each engine burn sequenced over the total elapsed mission time
modified linear characteristic	relationship between valve flow and valving element stroke that is comprised of a parabolic relation up to approximately 30% of stroke, followed by a linear relation up to 80 or 90% of stroke, with the remainder a square-root relation
MOV	main oxidizer valve
needle valve	valve with a long tapered needle for gradual opening or closing of the throat or shutoff when closed onto the seat
NA	not applicable
noncavitating valve	flow-control valve that operates in the noncavitating region to meter the flow of liquid propellant
OAMS	orbital attitude and maneuvering system
overtravel tolerance	feature of rotary valves such as the ball or blade whereby shutoff can be achieved even when the valving element is not rotated to exactly the same closure position each time
P_c	control pressure
parabolic characteristic	relationship between valve flow and valving element stroke in which flow varies with the square of stroke
pintle valve	flow-control unit utilizing a translating pointed shaft to change flow area through an orifice or flow passage
plunger solenoid	solenoid that pulls an armature into the center of a coil when the coil is energized

Term or Symbol	Definition
pneumatic	operated, moved, or effected by gas used to transmit energy
poppet valve	valve constructed to close off flow by translating a ball, cone, or disk against a seat in the housing. Translation of the poppet away from the seat can result in essentially orifice flow
pressurant	gas that provides ullage pressure in a propellant tank
pressure-ladder sequence	method to effect fail-safe engine starts by sequencing the operation of rocket engine control valves; the sequencing is achieved by vent mechanisms in the control system or propellant feed system or both that are triggered by pressure changes. The vent mechanism may be a burst diaphragm, a pressure actuator valve, or a sequence valve operated by valve motion. For example, when a burst diaphragm in a hypergol cartridge is ruptured by rising fuel feed-system pressure the propellants in the combustion chamber can be ignited.
pressure recovery	conversion of velocity head to pressure head in the section of the valve downstream of the throat; in cavitating flow-control valves, special diffuser sections are used to gain maximum pressure recovery
prevalve	valve located in the propulsion system between the vehicle propellant tankage and the main valves
primary leakage	leakage from the upstream side to the downstream side of a valving unit
primary seal	seal intended to limit primary leakage
proof test	pressure test to prove the structural integrity of a valve assembly without exceeding allowable stresses
PU	propellant utilization
Q	flowrate
rack and pinion	mechanical linkage for operation of a rotary valve in which the actuator shaft incorporates a straight-sided rack to drive a pinion gear attached to the rotary shaft
ramping	opening or closing of a valve controlled to achieve a desired flow-vs-time relation
random vibration	vibration characterized by a wide continuous band of multiple frequencies

Term or Symbol	Definition
RCS	reaction control system
redundant	incorporating duplicate, identical components to achieve increased reliability
repeatability	capability of a valving unit and actuator to operate in the same manner and in the same time each time the assembly is actuated
response time	period of time from first signal to full-open or full-closed position, a total comprised of electrical delay plus pneumatic or hydraulic control system delays plus valve travel time
Rockwell C	hardness scale
rolling element	the ball, needle, or tapered roller in a rolling-contact bearing
scch	standard cubic centimeters per hour
scim	standard cubic inches per minute
seat	surface in valve housing that valving element contacts to shut off flow and limit primary leakage
secondary leakage	leakage from valve interior to the exterior
secondary seal	seal that limits secondary leakage
self-aligning bearing	journal bearing with a spherical joint to provide alignment of the axis
shutoff valve	valve that terminates the flow of fluid; usually a two-way valve that is either fully open or fully closed
sleeve valve (linear)	valve utilizing a cylindrical sleeve element that reciprocates in the cylinder bore to open or close the flow area by uncovering or covering annular slots in the bore
sleeve valve (rotary)	valve utilizing concentrically mated slotted cylinders that open and close the flow area by rotation of one cylinder relative to the other
slotted crank	valving element linkage mechanism in which a slot in the lever of the rotating member holds the pin from the reciprocating actuator shaft so that linear actuator motion is translated to rotary without additional linkage to compensate for the change due to rotation

Term or Symbol	Definition
space-storable propellant	propellant with a vapor pressure such that the propellant can be stored in the space environment at moderate ullage pressure without significant loss over the mission duration
spool valve	valve with a solid cylindrical valving element having two or more lands that fit closely within the bore of the housing; the valve opens or closes by translating the spool within the bore to connect passages in the housing
square-root characteristic	relationship between valve flow and valving element stroke in which flow varies with the square root of the stroke; this characteristic is also termed "quick opening"
stall	condition wherein the actuation force is equal to the dynamic force plus the friction force, and the valving element stops in a partially open position
static seal	device used to prevent leakage of fluid through a mechanical joint in which there is no relative motion of the mating surfaces other than that induced by changes in the operating environment
sterilization	process in which a propulsion system package is rendered sterile or free from micro-organisms and bacteria by the application of heat or by the use of a special sterilization fluid or both
thermal-compensating orifice	orifice that adjusts the flow area to compensate for temperature changes in the controlled fluid
three-way valve	valve having three controlled ports, usually one inlet and two outlet ports
throttle valve	valve to control flowrate of a fluid by means of a variable-area flow restriction; the valve may have an infinite number of operating positions as contrasted to a shutoff valve that is either fully open or fully closed
timing	operation of a valve in a prescribed manner within a prescribed time
torquemotor	electrical motor of small rotary displacement that incorporates a control winding composed of two separate coils
travel time	elapsed time from valve first motion to full-open or full-closed position
triple point	the intersection of the solid/vapor, solid/liquid, and liquid/vapor lines in a phase diagram; at this point, solid, liquid, and vapor phases may coexist in equilibrium

Term or Symbol	Definition
turndown ratio	ratio of maximum to minimum controlled flowrates of a throttling valve
v	velocity
valving element	the moving portion of the valving unit that translates or rotates to vary flow or to shut off the flow of liquid
valving unit	combination of the movable valving element and the valve seat contained in a suitable housing
valving unit throat	flow area between the valving element and seat of the valving unit
visor valve	ball valve with only a segmented shell of the ball; this design reduces weight
warmant passages	passages provided in cryogenic-valve hydraulic actuators to maintain actuator temperatures above specified operating minimums under extended hold conditions
wet cycle	functional test in which the valve is operated with propellant or a test fluid in the flow passage
worm screw (or ball screw)	mechanical device used to convert rotary motion to reciprocating motion for positioning the valving element
y	valving element stroke
yoke	a cross member used in bipropellant valves of poppet design to connect the valving elements with a common actuator

Material[1]	Identification
Aerozine 50 or A-50	mixture of 50% hydrazine and 50% unsymmetrical dimethylhydrazine per MIL-P-27402
beryllium copper	heat-treatable copper alloy per AMS 4650
Buna-N	trade name for copolymer of butadiene and acrylonitrile
chlorine trifluoride	propellant oxidizer, propellant grade per MIL-P-27411
CRES	corrosion-resistant steel

[1] Additional information on metallic materials herein can be found in the 1972 SAE Handbook, SAE, Two Pennsylvania Plaza, New York, NY; and in MIL-HDBK-5B, Metallic Materials and Elements for Aerospace Vehicle Structures, Dept. of Defense, Washington, DC, Sept. 1971.

Material	Identification
DC 55	silicone grease manufactured by Dow Corning Co.
electrolytic nickel	nickel plate achieved by an electrolytic deposition process as distinguished from the chemical reduction process termed "electroless"
epoxy	thermosetting synthetic resin widely used as a potting material and as an adhesive
fluorine	elemental fluorine (F_2) in its liquid form used as a cryogenic propellant
GH_2	gaseous hydrogen
GN_2	gaseous nitrogen
Haynes 25	trade name of Haynes Stellite Corp. for a cobalt-chromium-nickel alloy
helium	pressurant helium (He) per MIL-P-27407
hydrazine	N_2H_4, propellant grade per MIL-P-26536
Inconel 625, 718	trade names of International Nickel Co. for austenitic nickel-base alloys
Invar	trade name of International Nickel Co. for a nickel-base alloy with a very low coefficient of thermal expansion
IRFNA	inhibited red fuming nitric acid, propellant grade per MIL-P-7254
Kel-F	trade name of 3M Corp. for a high-molecular-weight polymer of chlorotrifluoroethylene
LH_2	liquid hydrogen, propellant grade per MIL-P-27201A
LO_2 or LOX	liquid oxygen, propellant grade per MIL-P-25508D
methylene chloride	halogenated hydrocarbon solvent per MIL-D-6998
MMH	propellant monomethylhydrazine, propellant grade per MIL-P-27404
Mylar	trade name of E. I. duPont, Inc. for polyethylene terephthalate film
N_2O_4	nitrogen tetroxide, propellant grade per MIL-P-26539
N_2H_4	hydrazine, propellant grade per MIL-P-26536B
nitrogen	gaseous nitrogen per MIL-P-27401A

Material	Identification
nylon	generic name for a family of polyamide polymers
plastic	high-molecular-weight material that while usually firm and hard in its finished state is at some stage in its manufacture soft enough to be formed into a desired shape by application of heat or pressure or both
RP-1	kerosene-base hydrocarbon fuel, propellant grade per MIL-P-25576
Stellite	designation for a series of cobalt-tungsten-chromium-carbon alloys manufactured by Haynes Stellite Corporation
Teflon	trade name of E. I. duPont, Inc. for polymer of tetrafluoroethylene
trichloroethylene	halogenated hydrocarbon solvent per MIL-T-27602
431	martensitic stainless steel
440 C	martensitic stainless steel
2024-T4	wrought aluminum alloy with copper as the principal alloying element; T4 temper
6061-T6	wrought aluminum alloy with Mg and Si as principal alloying elements; T6 temper
9310	an electric-furnace steel alloy with 3% nickel and 1% chromium

Propulsion System, Engine, or Vehicle	Identification
AJ10-137	engine for Apollo Service Module; 22 000 lbf (97.9 kN) thrust; uses A-50/N_2O_4 manufactured by Aerojet Liquid Rocket Co.
AJ10-138	engine for transtage; 16 000 lbf (71.2 kN) thrust; uses A-50/N_2O_4; manufactured by Aerojet Liquid Rocket Co.
Apollo	manned mission to the moon
Apollo Service Module	upperstage of the Saturn V vehicle; utilizes AJ10-137 engine system
Atlas	launch vehicle using MA-5 engine system
Centaur	upper stage on Atlas or Titan; uses the RL10 engine system
F-1	engine for S-1C; 1 500 000 lbf (6.67 MN) thrust; uses RP-1/LOX; manufactured by Rocketdyne Div., Rockwell International

Propulsion System, Engine, or Vehicle	Identification
Gemini	manned spacecraft for extended earth orbital missions
Gemini RCS and OAMS	reaction control and maneuvering engines (designated SE-6 and SE-7 respectively) on the Gemini spacecraft
H-1	engine for S-IB; 200 000 lbf (890 kN) thrust; uses RP-1/LOX; manufactured by Rocketdyne Div., Rockwell International
Intelsat III thruster	engine for Intelsat III; 3.5 lbf (15.6 N) thrust; uses N_2H_4 as monopropellant; manufactured by TRW Systems
J-2	engine for S-II; 200 000 lbf (890 kN) thrust; uses LH_2/LOX; manufactured by Rocketdyne Div., Rockwell International
J-2S	uprated J-2; 250 000 lbf (1112 kN) thrust
LMAE	Lunar Module Ascent Engine; 3500 lbf (15.6 kN) thrust; uses A-50/N_2O_4; manufactured by Rocketdyne Div., Rockwell International
LMDE	Lunar Module Descent Engine; 9850 lbf (43.81 kN) thrust; uses A-50/N_2O_4; manufactured by TRW Systems
LR-87-AJ-5	engine for Titan 1st stage; 215 000 lbf (956 kN) thrust; uses A-50/N_2O_4; manufactured by Aerojet Liquid Rocket Co.
LR-91-AJ-5	engine for Titan 2nd stage; 100 000 lbf (445 kN) thrust; uses A-50/N_2O_4; manufactured by Aerojet Liquid Rocket Co.
Mariner	interplanetary probe spacecraft
M-1	engine designed and developed by Aerojet-General but not flightproven; 1 500 000 lbf (6.67 MN) thrust; used LH_2/LOX
MA-5	five-engine system for Atlas containing 2 booster, 2 vernier, and 1 sustainer engines; boosters provide 330 000 to 370 000 lbf (1468 to 1646 kN) thrust; uses RP-1/LOX; manufactured by Rocketdyne Div., Rockwell International
MB-3	engine for the Thor vehicle; 170 000 lbf (756 kN) thrust; uses RP-1/LOX; manufactured by Rocketdyne Div., Rockwell International
RL10	engine for Centaur; 15 000 lbf (66.7 kN) thrust; uses LH_2/LOX; manufactured by Pratt & Whitney Aircraft Division of United Aircraft

Propulsion System, Engine, or Vehicle	Identification
RS-14	upper stage engine for Minuteman; 300 lbf (1334 N) thrust; uses MMH/N_2O_4; manufactured by Rocketdyne Div., Rockwell International
RS-21	engine for MM71; 300 lbf (1.3 kN) thrust; uses MMH/N_2O_4; manufactured by Rocketdyne Div., Rockwell International
R4D-1	reaction control engine for Apollo Service Module; 100 lbf (445 N) thrust; uses MMH/N_2O_4; manufactured by Marquardt Corp.
R4D-2	reaction control engine for the Lunar Module; 100 lbf (445 N) thrust; uses MMH/N_2O_4; manufactured by Marquardt Corp.
S-IB	booster using a cluster of eight H-1 engines
S-IC	first stage (booster) of the Apollo Saturn V vehicle; uses five F-1 engines
S-II	second stage of the Apollo Saturn V vehicle; uses a cluster of five J-2 engines
S-IVB	third stage of the Apollo Saturn V vehicle; uses a single J-2 engine
Saturn V	launch vehicle for Apollo
SE-5	engine for attitude control; 50 lbf (222 N) thrust; uses MMH/N_2O_4; manufactured by Rocketdyne Div., Rockwell International
SE-6	engine for Gemini RCS; 25 lbf (111 N) thrust uses MMH/N_2O_4; manufactured by Rocketdyne Div., Rockwell International
SE-7	engine for Gemini OAMS; 85 to 100 lbf (378 to 445 N) thrust; uses MMH/N_2O_4; manufactured by Rocketdyne Div., Rockwell International
SE-8	engine for Apollo Command Module RCS; 93 lbf (414 N) thrust; uses MMH/N_2O_4; manufactured by Rocketdyne Div., Rockwell International
Thor	launch vehicle using MB-3 engine system
Titan III	launch vehicle using the LR-87-AJ-5 engines for the first stage booster and the LR-91-AJ-5 engine in the second stage
Transtage	upper stage used with the Titan III vehicle

Propulsion System, Engine, or Vehicle	Identification
8093	altitude control engine for Centaur; 1.5 lbf (6.67 N) thrust; uses H_2O_2 (monopropellant); manufactured by Bell Aerospace

Abbreviation	Identification
AFFTC	Air Force Flight Test Center (Edwards Air Force Base, CA)
AFRPL	Air Force Rocket Propulsion Laboratory
AIAA	American Institute of Aeronautics and Astronautics
ASLE	American Society of Lubrication Engineers
ASTM	American Society for Testing & Materials
IES	Illuminating Engineering Society
KSC	Kennedy Space Center
NAR	North American Rockwell Corporation (now Rockwell International, Inc)

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SP-8017	Magnetic Fields—Earth and Extraterrestrial, March 1969
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