CONF 880503--1

LA-UR -88-443

LA-UR--88-443

DE88 006467

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

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SUBMITTED TO: Third Topical Meeting, Tritium Technology in Fission, Fusion and Isotopic Applications, May 1-6, 1988, Toronto, Ontario, CANADA
To be published in Fusion Technology.

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A TRITIUM-COMPATIBLE PIEZOELECTRIC VALVE FOR THE TOKAMAK FUSION TEST REACTOR

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INTRODUCTION

In 1985 the Los Alamos National Laboratory undertook development and testing of a piezoelectric valve that would be suitable for a limited number of tritium gas injections at the Princeton Tokamak Fusion Test Reactor (TFTR). The technical objective was to develop a valve that could provide the full program of tritium gas injections planned for TFTR (~100) without leakage or degradation of performance due to tritium. If leakage across the valve seat or other performance degradation should develop, it was desirable to make compensating adjustments without disassembling the valve.

This work describes modifications made to a commercial piezoelectric valve to make it sufficiently tritium compatible for the TFTR tritium injection scenario. The results of testing the valve for leakage and performance following a series of progressively more severe tritium exposures are also presented. Finally, a proposal for a totally radiation-compatible piezoelectric valve, suitable for tritium-burning fusion machines of the future, is described.

THE PRINCETON HYDROGEN PIEZO VALVE

A commercial piezoelectric valve* has been used for hydrogen gas injections at both the Princeton Large Torus (PLT) and at the TFTR with excellent results. An elegant computer control system, capable of real-time flow rate adjustments in response to plasma parameters, was developed[1] for the valve. Thus, though the piezoelectric hydrogen injection valve contains many materials that are not tritium compatible, it is highly desirable to develop a valve which can be operated from the existing control system. Moreover piezoelectric actuation is the only means known for making predictable, high-speed responses to real-time control in the large, varying magnetic fields surrounding a tokamak. For the TFTR application tritium compatibility is adequate if the outer case is impervious to tritium, and if performance is not degraded significantly during the anticipated schedule of 125 gas injections[2] as specified in Table I.

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*Precision Leak Valve PV-10, Veeco Instruments Inc., Terminal Drive, Plainview, NY 11803.

TABLE I

TFTR TRITIUM INJECTIONS BY PIEZO VALVE

(Total Pressure Constant at 1500 Torr)

No. of Shots in Series	TRITIUM %	TRITIUM Press. (atm)	TRITIUM EXPOSURE Per Shot (atm-hr)	TRITIUM EXPOSURE Total (atm-hr)
25	0.1	0.002	0.0002	0.005
25	1.0	0.02	0.002	0.050
25	2.5	0.05	0.005	0.125
25	10.0	0.20	0.02	0.500
25	100.0	2.00	0.20	5.000
	TOTALS			5.680

There are three areas of concern when using piezoelectric valves to inject tritium gas mixtures: (1) The presence of an ionizing gas in the space between surfaces separated by high d.c. voltages might cause current leakage or voltage breakdown, with unpredictable effects on valve performance; (2) the radiolysis of organic materials by tritium yields gaseous by-products that might introduce unacceptable levels of high-Z impurities into the plasma; (3) to the extent that proper valve operation depends upon the properties of an elastomer, the performance will deteriorate as the elastomer is degraded by tritium exposure.

The problem of electrical breakdown in the presence of tritium was investigated[3] during the initial testing of the TFTR Tritium Storage and Delivery System (TSDS). These tests indicated no significant charge leakage from the piezo crystal when using tritium at 2 atm and operating voltages as high as +250 v. The tritium exposure (42 atm-days) and the operating voltage (250 v) represent substantial overtests for the currently anticipated scenario. The matter of impurity buildup was also investigated by the TSDS fabrication team.[3,4] Ordinary hydrogen (protium) was the major exchange impurity observed after exposing the TFTR hydrogen piezo valve to pure tritium continuously for 15 hours, although 0.03 at.% of carbon (as methane) was also detected. Since unbaked, as-manufacturered, piezoelectric valves do not give rise to unacceptable quantities of high-Z impurities, and since any reduction of organics in the valve for tritium compatibility should reduce these impurities further, this problem appears to require no special attention.

Despite the assurances above, the TFTR hydrogen valve has three serious shortcomings for the tritium injection program: (1) its tritium compatibility should be improved to ensure reliable performance throughout the anticipated schedule of tritium injections; (2) the maximum flow rate of the valve is too small by a factor of 10. and past efforts to redesign the TFTR valve for increased throughput have met with only limited success; and (3) the valve requires complete disassembly and a delicate 3-screw adjustment to compensate for seat deterioration--an unacceptable feature for a valve that might require such adjustments after preliminary testing with tritium.

THE TFTR TRITIUM INJECTION VALVE

The solution to all three problems was to purchase and modify a piezoelectric valve of a new design from a different manufacturer.* This new valve (Fig. 1), as purchased from the manufacturer, has a flow rate adequate for the TFTR requirements, and it also features an external, single-screw adjustment to compensate for any changes in the valve seat material. The construction of the valve is such that all static elastomeric seals in the outer case can be easily replaced with metal seals.

The use of two relatively radiation-resistant organic materials for piezo valve seats was the subject of a recent paper.[5] The authors analyzed (but did not actually test) two materials for which tritium effects on sealing properties had been independently established[6] --ethylene propylene rubber (EPDM), and high density polyethylene (HDPE). EPDM has elastic properties similar to Viton, a common fluoroelastomer that has already been used successfully in thousands of these valves. EPDM is also usable at the TFTR bakeout temperature of 150° C. HDPE has a compressional modulus approximately 100 times higher than that of normal elastomers and it has poor high-temperature properties. EPDM elastomer therefore appeared to be the best choice for quick development of a low-risk piezolectric valve. The valve seat disk and other internal elastomers were thus replaced with EPDM, which is also expected to meet the TFTR requirements of low outgassing of high-Z gases under tritium exposure.

Because compression set and loss of elasticity in the valve seat is certain to result from exposure to tritium, threshold holding voltage will also change, and there should exist a convenient means of adjusting the nozzle-seat geometry of the valve. As previously stated, the TFTR tritium-compatible piezoelectric valve has an external single-screw adjustment for this purpose. This piston-type adjusting mechanism requires two more EPDM o-rings in the valve, which complicates the task of tritium hardening. Nevertheless the maximum adjustment allowed in the

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*Model MV-112 Piezoelectric Gas Leak Valve, MaxTek Inc., 2908 Oregon Ct., Torrance, CA 90503

TABLE II

MAXTEK MV-112 PIEZO VALVE

MATERIAL SUBSTITUTIONS FOR COMPATIBILITY

PART	ORIGINAL MATERIAL	MAT'L PROBLEM	REPLACE WITH
FITTING O-RINGS	VITON	T	WELD IN
ADJUSTER O-RINGS	VITON	T	EPDM
WIRE INSULATION	TEFLON	TT	KAPTAN
PRELOAD BALL	TEFLON	TT	CERAMIC
PRELOAD SPRING	400 SS	M	OK
SPACER O-RING	VITON	TT	EPDM
MAIN BODY O-RING	VITON	TT	ALUMINUM
CRYSTAL BONDING	EPOXY	T	OK
CRYSTAL PLATING	NICKEL	M	SILVER
VALVE SEAL DISK	VITON	TT	EPDM
ADJUSTER SPRING	400 SS	M	OK
BNC CONNECTOR	TEFLON	TT	CERAMIC
CONNECTOR O-RING	VITON	T	WELD IN

KEY TO MATERIAL PROBLEM:
M - SLIGHTLY MAGNETIC
T - TRITIUM INCOMPATIBILITY--MINOR
TT - TRITIUM INCOMPATIBILITY--MAJOR

standard valve is only 0.15 mm. and even a moderately hard o-ring should tolerate this. Table II identifies all the components of the valve that are incompatible either with tritium or with the high magnetic field, along with the material substitutions proposed.

The staff of TFTR tested an unmodified valve and determined that it met their basic flow requirements (50 torr L/s at 1500 torr inlet pressure and 150 vdc actuation)[7]. Two specially modified valves were then purchased: one for tritium testing at Los Alamos, and the other for further hardening by elimination of all unnecessary elastomers. The only modifications made to these valves by the manufacturer were to replace all fluoroelastomer parts with EPDM, and to substitute nonmagnetic silver for the standard nickel plating on the piezoelectric crystal.

TRITIUM EXPOSURE AND INJECTION TESTS

At Los Alamos we conducted 9 series of 25 gas injections on one of the factory-modified valves, starting with 2 deuterium runs to establish basic valve performance, and gradually building up to 2 series of shots with pure tritium. Valve operating pulse parameters were kept constant (150 vdc for 450 ms) throughout the entire experimental program. Each 25-shot series was conducted in a single day, but the entire test program extended from March through June, 1987, with six weeks elapsing between the two pure-tritium runs. A final postexposure series was conducted with deuterium five months after the last tritium exposure and shot series. Table III summarizes the pertinent data from all these experiments.

TABLE III

PIEZO VALVE TRITIUM TESTS (DATA SUMMARY)

Run No.	DATE	% Trit	Q/Shot Torr-L	Std Dev	Q(Tot) Torr-L	Torr -Hr
1	3/19/87	0.00	24.43	.15	109	0
2	3/19/87	0.00	25.03	.41	375	0
3	3/24/87	0.10	28.61	.14	713	7
4	3/26/87	1.02	29.27	.06	731	31
5	4/02/87	2.43	30.47	.07	761	73
6	4/09/87	9.86	31.09	.30	766	250
7	5/13/87	98.66	24.58	.09	613	2021
8	6/29/87	98.65	22.73	.21	524	1007
9	11/23/87	0.00	38.70	.77	967	0
TOTAL TRITIUM EXPOSURE:						3390

A constant throughput per pulse was observed for each series of shots, for which the typical scatter is 0.2-0.5%. The variation of mean throughput from one series to the next is significant and not altogether understood. It may be related to the effects of compression set of the EPDM valve seat material, but the conductance of the valve appears to increase between early runs in the series, whereas it decreases between runs 6, 7, and 8. This decrease may be associated with hardening of the elastomer, as these runs represent the most severe exposures to tritium. The throughput increased substantially for the final deuteruim run (No. 9) - more than can be accounted for by the M. W. difference between tritium and deuteruim (see next paragraph). The time modulation is linear and reproducible down to pulses of a few ms duration, so lower flow rates can be accurately obtained from the same valve. No significant deterioration in valve performance was detected during the Los Alamos tritium exposure and testing, and the available external adjustment was not needed in the course of these experiments.

In addition to the tabulated data, we report the following observations, which are important for the design of gas injector systems. In Run #4 (10% tritium, nominal) the tritium concentration actually varied from ~20% in shot #1 to ~5% in shot #25. This variation in concentration was an unavoidable result of our gas mixing method for all of our mixed isotope runs. We also observed a small but statistically significant increase in throughput per pulse as we progressed through this series. The conductance formula for viscous flow through an aperture contains a reciprocal square-root-of-molecular-weight term,[8] and this effect is reflected in these data (increasing flow rate with decreasing mean molecular weight).

The second observation was that the closed test valve leaked a small quantity of gas across the seat whenever high pressure (1500 torr) was introduced suddenly to its inlet port. This characteristic is inherent in the design of this and most piezoelectric valves. Although the crystal bimorph is pressure balanced in any static configuration, a transient differential pressure on the diaphragm can deflect it enough to allow a small quantity (20-25 torr-L) of gas to flow past the valve seat. This effect was only observed on initial pressurization of the previously evacuated valve, and no valve leakage was detected on subsequent repressurizations (from 1400 torr to 1500 torr).

The third observation relates to permeation of tritium through elastomers. Because the Los Alamos tritium exposure tests were conducted in a purgeable glovebox, there was no attempt to replace the elastomeric static seals in the outer valve body. When tritium concentration was increased to 100%, the tritium concentration in the glovebox increased significantly, corresponding to a tritium leak rate of 10^{-6} atm mL/s. The leak appeared to come from the vicinity of the piezoelectric valve, but it could not be identified with any particular seal. We believe that this represents the cumulative permeation through all the elastomers in the unmodified valve body. This confirms the requirement that all elastomer seals in the outer body be replaced with weldments or all-metal compression seals, for which the permeation rates are insignificant at operating conditions.

PROPOSAL FOR A COMPLETELY TRITIUM-COMPATIBLE PIEZOELECTRIC VALVE

A completely tritium-compatible piezoelectric valve was also proposed as a result of this study. This proposal (Fig. 2) is based on further modifications to the same commercially available piezo valve that was tested for TFTR. It features fabrication from inorganic materials, including a sapphire valve seat and a metal-bellows-sealed crystal preload adjustment. The company that manufactures the piezo valve described in this study has had limited success with a sapphire-seat piezo valve,[9] but extensive development and testing would be required to ensure that such a valve met the performance, reliability, and seal integrity requirements relevant to tokamak tritium injections. This proposal was somewhat more ambitious than required for the TFTR experiments, but is a desirable development for future fusion machines, for which the gas injectors will receive intense and chronic exposure from tritium, as well as from the much more intense radiations emanating from the DT-burning plasma.

CONCLUSIONS

A commercial piezoelectric gas injection valve was modified for enhanced tritium compatibility and tested with tritium for the anticipated program of tritium gas injections at TFTR. The valve tested provides the required maximum throughput of tritium gas (50 torr-L/sec) under operating parameters available from the TFTR computer control system and the TSDS tritium system. The valve's short-term repeatability is excellent when the injected pulse is controlled by time modulation at constant voltage. The time modulation is linear and reproducible down to pulses of a few ms duration, so the lower flow rates can be accurately obtained from the same valve. No significant deterioration in valve performance was detected in the course of the Los Alamos tritium exposure testing, which duplicated the schedule of exposures and injections the valve will see at TFTR. Static all-metal case seals, identical to those already qualified for tritium in TSTA applications, can be installed without changing the valve's functional design or affecting its operational performance.

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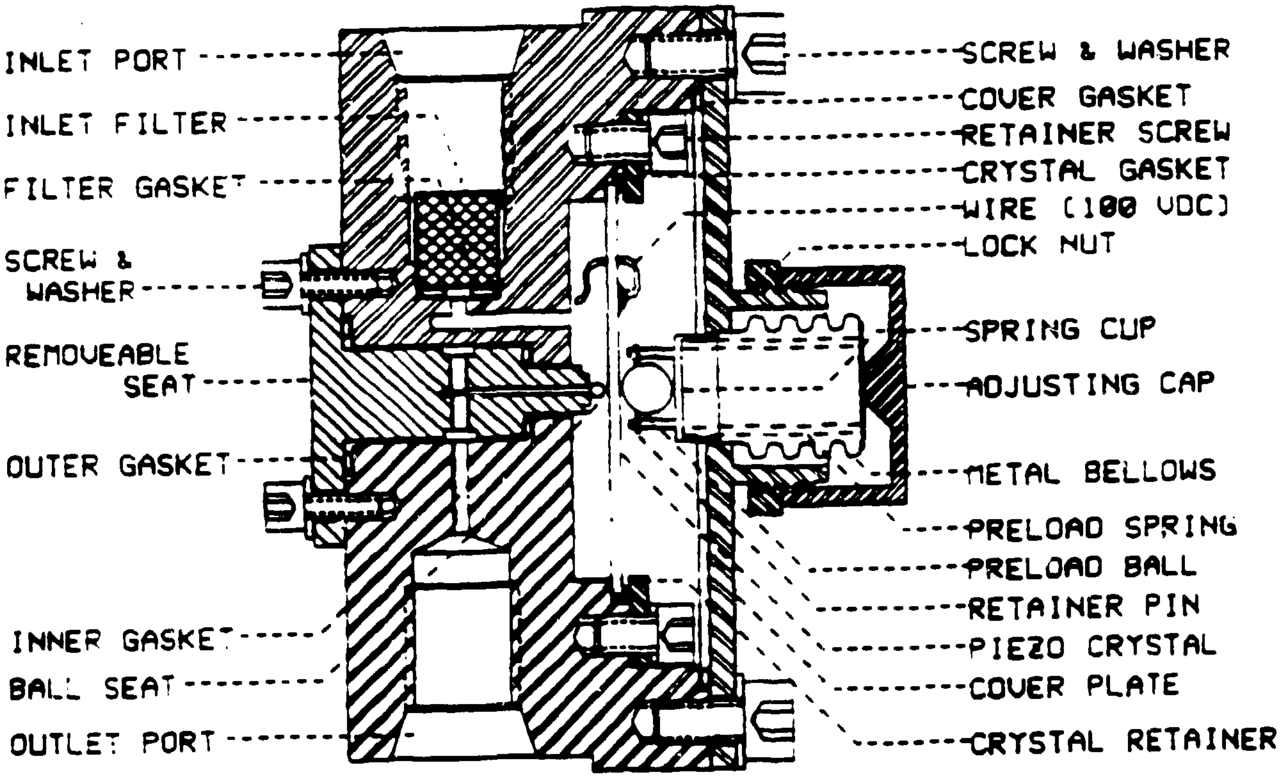
Fig. 2. Concept for a completely tritium-compatible piezoelectric valve.



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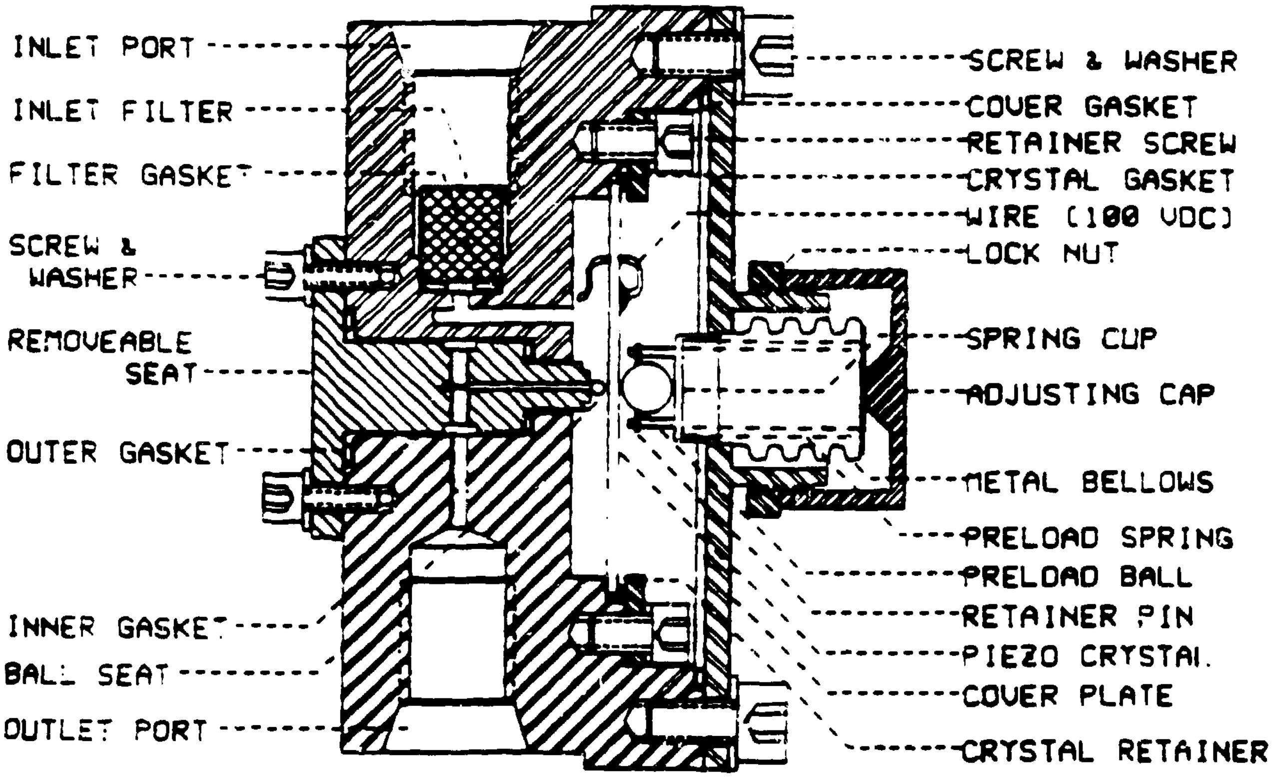
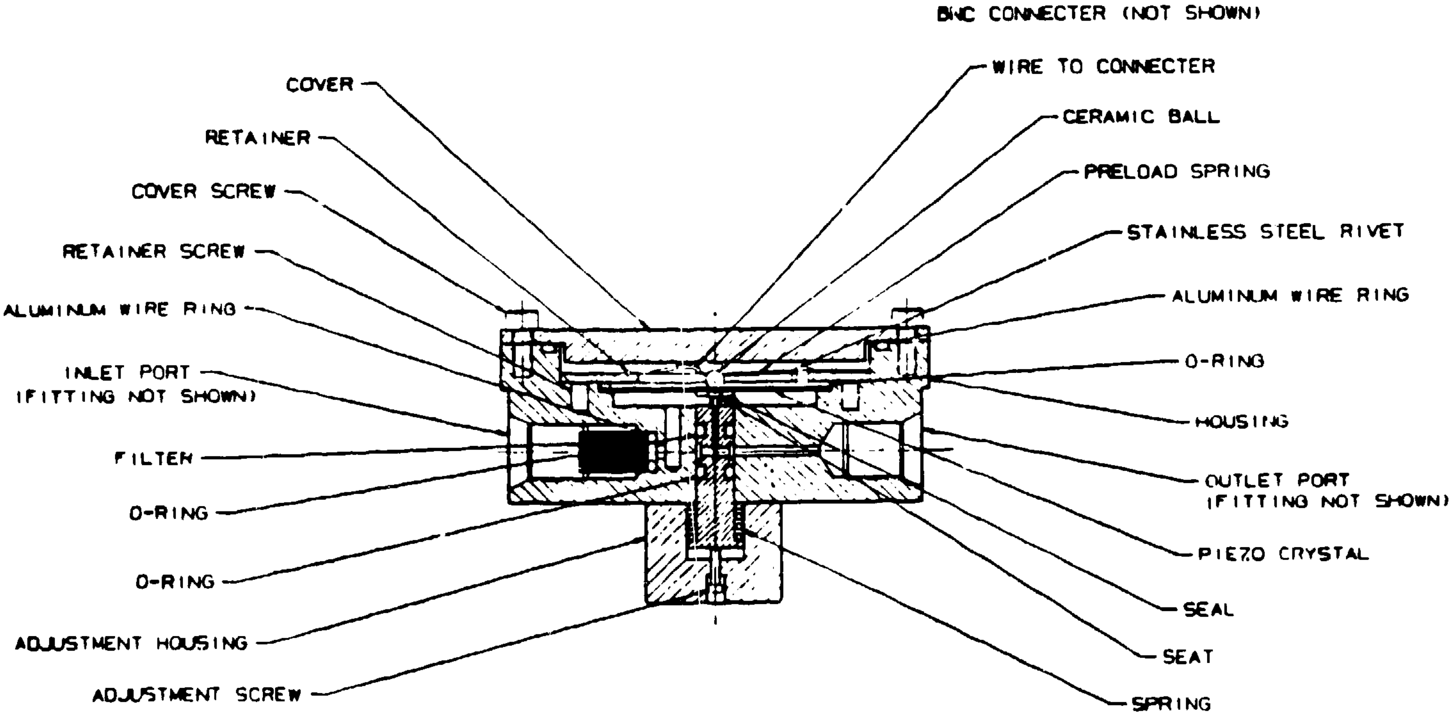


Fig. 1. The TFTR tritium-hardened piezoelectric valve.



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