OFFICE OF NUCLEAR SAFETY

TECHNICAL NOTICE

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Guidelines for Valves in Tritium Service

Introduction

In early 1991, the Secretary of Energy formed a task group to review all aspects of operations at Department of Energy (DOE) tritium facilities and to recommend measures to reduce the number of tritium releases and worker exposures. One observation of the task group was that no clearly defined design criteria existed and no operational standards had been established throughout the tritium complex.' Compounding this situation was a poor communication process throughout the tritium complex. In response to this situation, the Program Secretarial Officer formed the Tritium Focus Group composed of representatives from all the DOE tritium handling facilities and applicable Headquarters personnel, One objective of the Group is to foster communication of applicable topics of interest across the complex.

This technical notice is another method of disseminating information. Input was drawn primarily from the tritium facilities at the Savannah River Site, Mound Laboratories, and Los Alamos National Laboratory. Experience is also included from the Pinellas Tritium Recovery facility; Lawrence Livermore National Laboratory; Sandia National Laboratory, Livermore; Princeton Plasma Physics Laboratory; and the Ontario Hydro Tritium Laboratory, Canada. While this notice generally addresses experiences and useful practices associated with tritium systems and components, it concentrates on valves used in tritium service.

Most valves used in tritium service are small globe valves less than one inch in diameter. The vast majority of them are manufactured by Nupro, one of the Swagelok companies. Because Nupro valves are used so often, most of the failures discussed will involve Nupro valves and most recommendations will use Nupro-specific nomenclature. There has been no attempt to ascertain product reliability (which includes both failure and operating data) of Nupro valves or those of any other manufacturer.

Nupro differentiates valves not only by size but also by material of construction, seating surface material, body-to-bonnet connection type (gasket or welded), actuator type, end-connector type, and series (e.g., B indicates bellows, U designates a bellows-sealed valve with secondary stem sealing). For example, the Nupro valve specification SS-12UG-TW-8C designates stainless steel for all wetted parts except the stem tip, which is 3/4-inch stellite[a], bellows with secondary stem sealing, body-to-bonnet gasket connection, weld-end connected, normally closed-air activated. The suffix T1 (one port) or T2 (two ports) at the end of these designators would indicate a bonnet sniffer tube for monitoring bellows integrity. The bonnet sniffer attachment is not well suited for vacuum systems because the sniffer must be held at a lower pressure than the system side of the bellows in order to continuously monitor leakages, which requires extensive support.

It is important to match hardware to its intended function. Some tritium leaks were the result of selecting an inappropriate valve; others resulted from older, deteriorated valve seats; and still others were caused mostly by operational errors.

Some undesirable practices and misapplications that caused valve-related failures are examined here and future courses of action are recommended to avoid repetition of these events. Also, desirable valve characteristics and practices that should be considered when selecting valves for use in tritium service are discussed. Supporting logic for the desirability of these features is presented by discussing the mechanisms of valve degradation followed by examples of related events. This discussion concludes by grouping desirable valve and system features and operational actions into two categories: strongly recommended and recommended. Continuing data collection activities will form the basis for future corrective action recommendations.

Mechanisms of Valve Degradation

Two general degradation mechanisms exist with tritium: one from beta radiation and the other from hydrogen/helium embrittlement. Beta radiation has more impact on polymers, while hydrogen/helium embrittlement is more of a concern with metals at higher temperatures and pressures. The six-kev tritium beta particle can easily break the strongest organic bonds; therefore, the useful life of most polymers is limited when exposed to tritium. Valves used in extensive tritium service should either be designed with features and materials that minimize the effect of radiation on performance, or an appropriate preventive maintenance schedule must be established. The seat-sealing surfaces, gaskets, and any packing should be composed of tritium resistant-materials. If polymer seals are used, tritium exposure must be minimized by the valve design. The valve chosen should have characteristics consistent with its overall service requirements.

Polyimides such as VESPEL" SP-1 (DuPont) are shown to be more radiation-resistant than most polymers; but, in some applications, softer, more deformable polymers such as polychlorotrifluoroethylene, Kel-F" (3M Company) are desirable. However, halogenated polymers produce corrosive gases (e.g., hydrogen chloride, hydrogen fluoride) that attack system components. Care should be taken to specify gaskets of non-halogenated material. A preventive maintenance replacement program for valves containing these polymers will help ensure functionality,[b] but it is better not to use them.[2,3] Replacing halogenated components only provides a fresh source for production of gaseous acids that degrade system materials.

In addition to VESPEL", Ultra-High Molecular-Weight Polyethylene (UHMWPE) appears to be an acceptable alternative to halogenated polymers. One Department of Energy (DOE) facility selected this type of polyethylene for use as stem tip material (i.e., the sealing surface) because UHMWPE was shown to be resistant to gamma radiation. While this is a desirable characteristic, the overriding concern with radiation damage from tritium is the soluble permeation of hydrogen isotopes. Even though penetration depth is on the order of a half micron, tritium will dissolve into the polymer and take the place of hydrogen in the matrix. The gamma exposure data for UHMWPE only addresses the ability to withstand bond breakage but not the reconstitution of the bonding process for interstitially dissolved materials. The UHMWPE operating experience at this facility should help establish its survivability.

Another drawback associated with the polymers under consideration for use is the intrinsic small percentage of water content that is available for exchange with tritium oxide. Surface area can be minimized by design only to a degree. Vacuum baking valves prior to service to remove water content is only partially effective.

Metals are not affected by this oxide exchange mechanism and beta radiation has little or no effect on metal. Valves with metal stem tip to metal seat (e.g., stainless steel to stainless steel, stellite to stainless steel, copper to stainless steel) and metal gaskets (e.g., silver-plated gaskets) are therefore preferred for many applications. Austenitic stainless steels are superior to ferritic steels in regard to hydrogen/helium embrittlement. Stainless steel should be specified as the base material for all valve bodies regardless of stem tip material.

Another degrading effect on valve performance is particulate buildup on stem tips, which causes scoring and channeling on sealing surfaces. The immediate impact of particulate buildup may be less severe on polymer stem tips because the particulates can become embedded in the tip material and not score the sealing surfaces to the degree that buildup on a metal surface would. However, cumulative exposure of the polymer to the tritium in the embedded particulates will eventually be deleterious.

Applicable Tritium Release Events

The tritium release on April 2, 1991, at the Lawrence Livermore National Laboratory[4] was caused by tritium degradation of the elastomer seat sealing surface of a tritium isolation valve. Seat sealing failure resulted in pressurizing the fittings downstream of the valve and an accumulation of tritiated water in a section of the fittings.

In a related failure mechanism at Sandia Livermore, a teflon seat in a pressure regulator valve on a deuterium/tritium bottle cracked after exposure to the 800 pounds per square inch (psi) gas mixture. Operations personnel did not realize that the pressure regulator contained teflon and therefore took no special precautions.[5]

The elastomer seat sealing failure at Lawrence Livermore was exposed to many times more than its qualified cumulative dose, so it is not surprising that it failed. It is surprising, though, that at least four DOE facilities recently experienced seat leakages in VESPEL™-tipped valves. One of these facilities operated with system pressures at 80 psi. It appears that there is a synergetic failure mechanism associated with system pressure operating on polymer sealing surfaces that are closed for long periods of time.

VESPEL" is relatively stiff (softer than copper, harder than Kel-F" and UHMWPE), so it is likely that deformed sealing surfaces were a contributing cause to these failures. In one instance, it appeared that the stem tip was wedged in with too much force and, over time, this resulted in a deformed sealing fit.[6] In another, valves were kept closed for long periods of time, possibly leading to deformation.' Maintenance personnel should be aware of this potential for deformation when storing or carrying spare valves in the closed position. In addition, misalignment of the stem tip with the seating surface may have contributed to these failures. Continued collection of VESPEL" performance data will widen our knowledge regarding reliability of this material in tritium service.

Stem wedging or excessive torque is more apparent as a root cause of seat leakage with metal-to-metal surfaces. Two events involving manual valves illustrate this type of failure: a uranium trap leakage from an SS-6BW valve on an Amersham container on 8 January 1990 at Mound' and the Tritium System Test Assembly (TSTA) release on 28 March 1991 that occurred from a container across an SS-4H Nupro valve. The SS-4H valve was not new, but its operating history is unknown.' It was not tested prior to placing it in service (i.e., attached to the container). Examination of the failed valve indicated that the seating surface had considerable deformation." A likely cause was excessive manually applied torque.

Although a similar root-cause analysis was not performed for the leak across the isolation valve seat of the uranium trap, it appears that the SS-6BW valve may have been deformed by excessive torque also. (A discussion of possible contributing cause, that of particulate buildup, follows.) Valves in tritium service are normally less than one inch in diameter, so it is relatively easy to apply too much torque.

Torque required to close a valve is dependent on factors such as valve size, mechanical design, stem tip and valve seat materials, and service conditions. All manual valves cycled and used to contain tritium should be fitted with torque limiters (e.g., calibrated slip wrenches, spring-loaded ratchet handles, T-handle hex nuts, clutches).

When copper stem tip valves on Amersham shipping containers at the Ontario Hydro Tritium Laboratory leaked, the cause was traced to faulty filters upstream of the uranium beds.[c] Degradation from particulate buildup and subsequent scoring of sealing surfaces was most likely caused by carryover from the hydride beds. It is likely that particulates accumulate to the greatest extent on the stem tip of the valve closest to the hydride bed as this is the location of the first change in flow direction.

Desirable Features

The following features are desirable for valves used in tritium service.

Packless Design

It is more desirable to use packless designs, either metal-bellows valves or metal-diaphragm valves, than tritium-resistant packing material. Valves with no moving seals are preferable to those with packing because packing wears from normal use, is subject to radiation-induced damage, and requires periodic adjustment. Metal-bellows valves are preferred for most tritium applications, and this design is discussed throughout. Metal bellows are extremely effective for lower pressure applications, including vacuum operations. However, metal-diaphragm valves are preferred for higher pressure applications (1,000 to 3,000 psi).

Diaphragm valves are easier to decontaminate because there are no convoluted internal surface areas as in globe valves. Recent experience with metal diaphragm valves at Mound indicates successful sealing at pressures of 1,500 to 3,000 psi. Valve leakage caused by misalignment may be more pronounced in diaphragm valves. These valves have stem tips that are rigidly attached to stiff diaphragms and, therefore, are less forgiving to seat misalignment than metal-bellows valves. This can result in an initial need for a larger valve sample in order to obtain an acceptable number that pass the leak test. Additional data is needed on misalignment degradation over the service life of valves that were initially leak-rate acceptable. Practices and precautions for using diaphragm valves may be recommended as a result of the Mound experience.

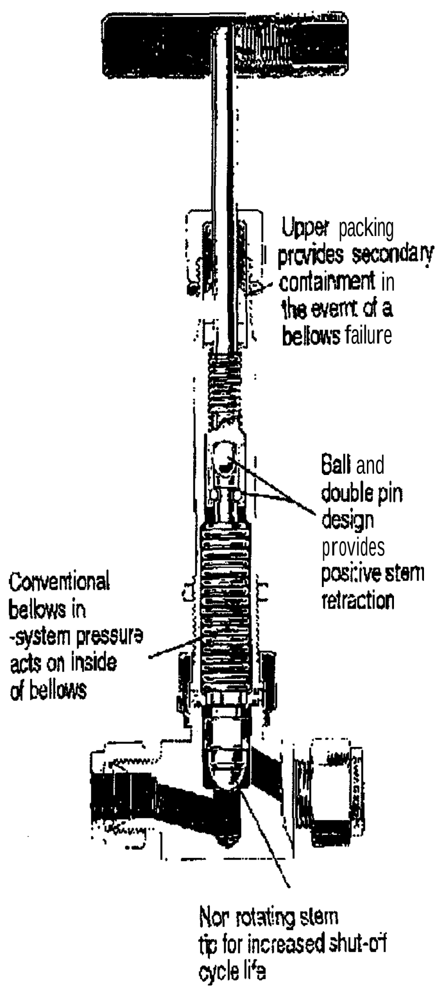
Secondary Containment

Secondary, or backup, containment is another desirable feature for valves used with tritium. For example, the Nupro U series of valves are designed with a backup barrier for containment. (See figure) Primary stem sealing is provided by a nesting-type, welded-metal bellows; and, if the bellows fails, a spring-energized teflon seal provides secondary sealing.

Teflon is permeable to tritium; but, if its cumulative dose from tritium beta is relatively minor, it will be superior to a single barrier because a smaller amount of tritium is passed when there is a primary barrier failure. That amount should be rapidly detected indicating a leak in the valve. If the cumulative dose on the teflon seal is relatively large (e.g., the leak was not detected by a sniffer tube), sealing capability disappears. Future advances may result in better secondary sealing materials for tritium. A likely application for secondary containment valves is on portable or product containers under pressure.

Stem Tip Design

Hemispherically shaped stem tips are a desirable internal design feature in valves. This feature is related to the issue of excessive torque applied to manual valves. The hemispheric shape provides a broader sealing area for the valve seat, which is important for manual valves that have some pitting and galling caused by excessive torque or any valves that contain misalignments between the stem and seat. The harder the material of the stem tip and seat, the less pliable and less forgiving the valve is to such misalignment. Metal-to-metal valves tend to benefit the most from the hemispheric design; although manual VESPEL” valves, which now possess only



Nupro U Series Bellows Valve

conical stem tips, might also appear to benefit from the hemispheric design.

Materials of Different Hardness

Using materials of different hardness in the stem tip and valve seat results in better sealing because the softer material deforms and conforms to the surface of the harder material, thus reducing galling and pitting. For example, a stainless-steel seat used in conjunction with a stellite tip will cold work the seat; or a copper tip work hardened by exercise with a stainless-steel seat is preferable to a stainless-steel seat and stem tip combination. Although not used extensively in the DOE complex, copper-tipped valves have an outstanding operating record. At least three tritium facilities reported reliable performance from copper-tipped valves. Extensive Canadian experience confirms this reliability.[c] Although copper cannot be used when mercury is present, use of mercury in tritium systems is declining rapidly.

Stem Concentricity

Some DOE facilities reported misaligned (i.e., seat and stem were not coaxial) valve shafts that prevented the stem tip from mating precisely with the valve seat. Eventually, if not immediately, this caused the valve to leak across the seat. Personnel at one facility said they routinely disassemble valves and check shaft alignment. While disassembly and inspection of stem concentricity is not advocated, a quality assurance receipt program requiring inspection of 100 percent of valves received from the manufacturer is recommended. Such a program is particularly important because many component manufacturers do not allow customer quality assurance representatives to observe manufacturing and assembly processes. Therefore, receipt inspection is important not only to detect component defects but to validate that the valve received is the valve ordered.

The DOE Office of Nuclear Safety required verification of stem tip material on installed isolation valves before concurring in a facility startup. Valves with UHMWPE stem tips were ordered, but the facility had no documented quality receipt inspections and the valve bodies were stamped with identifiers indicating Kel-F'" stem tips. It is not uncommon to receive valves inconsistent with order specifications. The Ontario Hydro Tritium Laboratory, for instance, received different valves than those specified on orders frequently enough to institute a policy of ordering stock valves along with specified components.[c] They then disassemble the stock valve and reassemble it in the desired configuration.

The facility that checks alignments had a recent event" involving non-coaxial shafts, which may be the motivation behind its inspection program. A facility-specific design feature combined with some non-coaxial shafts resulted in a common-cause failure of multiple valves to close. The valves (SS-4BK-VP-1C) were modified to fit valve position indication requirements of the facility. A valve-stem extender was added that produced a second bushing point with a tight tolerance. Once opened, some of the valves would not close. These valves had misaligned stem shafts that were binding at the new bushing point and there was insufficient spring force to overcome the binding. VESPEL" stem tips require more spring force than the comparably sized Kel-F" valves, which is the standard stem tip provided by the manufacturer for this size valve. Adding a second spring to the valves with misaligned shafts or using all coaxial valve stems (even with one spring) solved the problem. As a result of Nuclear Safety inquiries regarding the event, the manufacturer developed a pre-seating procedure and an alternate field procedure for one-spring VESPEL'" valves (i.e., the series 1 air actuator for 1/4-inch valves) for use in conjunction with stem tip replacement."

Pre-seating should be performed on applicable VESPEL" valves in accordance with manufacturer recommendations. Some newer designs, such as the Nupro BN valve, incorporate improvements in stem guide methodology that reduces misalignment incidents but does not preclude the need for pre-seating. Externally guided stem tip valves are more suited to manual applications than remote valves in which the rod extends throughout the actuator housing.

Throughput leaks with BN type valves have been experienced at TFTR. The relatively narrow (compared to other type valves such as BK) landing area of the BNs coupled with its light spring force makes these valves more susceptible to damage or imperfections of the sealing surfaces. Observed sealing problems were due to either imbedded metallic particulates, and/or machining ring marks (generated during the manufacturing process of the valve stem tip). Metallic particulates had been observed on the valve sealing surfaces. These particulates may have been generated from the body to bonnet tapered mating surface during valve reassembly after welding operations. These stainless steel gallings may become attracted to the VESPEL"" surfaces due to static charge, and once on the surface, they become ingrained. The machining grooves on the VESPEL" sealing surfaces effect BN valves more than other Nupro valves, due in part to the increased probability of the machine grooves impacting the entire small width landing areas. The TFTR fix included additional spring force (i.e., helper spring) after running in the seat. Just running in the seat without the additional spring force does not appear to be sufficient to keep the VESPEL" deformed to the extent necessary to overcome the machine grooves. This and other aspects of the TFTR BN valve experience are described in a report, soon to be published by Princeton Plasma Physics Laboratory.

Valve Stroke Control

Appropriate actuator strength and closure force for remotely actuated valves are required for optimal performance. Excessive torque applied to metal stem tip manual valves leads to eventual seat leakage. A somewhat analogous situation can result for remotely actuated valves if the actuator jams or wedges the stem tip into the sealing surface. The stroke of the valve can be slowed before closing, resulting in a softer impact for stem tips. For example, restricters of air flow into or out of the actuator, depending on whether the valve is designed to open or close with air pressure, can slow the stroke. In situations where closure time is not critical, the entire closure cycle can be slowed by using smaller diameter tubing or lower actuator pressures. Generally, hard metal is used for manual valves and polymers and soft metals for remote valves; however, there have been successes outside this convention. In fact, operating experience at one facility has been failure-free with pneumatically actuated stellite valves, which can be attributed in large measure to a soft-landing design. Another reason for this excellent record may be careful machining by facility personnel of the stellite stem tips used in the remote valves.

In addition to the beneficial impact on the seat, the bellows of a soft-impact valve won't flex and stress as rapidly as hard-closing valves. Failure data on bellows, especially in a tritium environment that should accelerate the failure process, is not readily available. Soft-landing bellows may exhibit better durability than hard-landing bellows. A bonnet sniffer tube with valves having inspection ports is recommended for detecting bellows failures that could result in undesirable consequences. However, failure of the bellows may not necessarily be a failure mechanism of interest. For example, if the valve is performing an isolation function for a specified condition such as a seismic event, bellows failure is immaterial because it is assumed that downstream piping not qualified for a seismic event will fail. Integrity of the seal is the only failure mechanism of interest in this situation.

Fail-Safe Designs and Diversity

System configurations should be designed with fail-safe valves that have the least amount of spring travel possible. The smaller the spring distance travelled, the less chance there is of the valve being held up. For example, if the fail-safe position of an air-actuated valve is closed, then it would open with air pressure and spring closed when air pressure is removed. Normally, a spring-to-close design is used when the fail-safe position is closed; however, diversity is a thing of value. If two valves in series can both perform the desired function (e.g., isolation), it may be desirable to have one valve that springs to open (air pressure to close) and the other valve that springs to close (air pressure to open). This diversity guards against some common-cause failure mechanisms. The design decision is a function of the specific application, valve failure probabilities, mitigation features, and consequences of valve failures.

Desirable Practices

It is helpful if manufacturers of valves used in tritium systems minimize the number of field welds by welding as many fittings and stubs as possible at the factory. This reduces valve seat warpage that can result if heat from the welding operation is not dissipated properly, which sometimes occurs in field welds.

Specification of low-carbon stainless steel (316L or 304L) is desirable when selecting system materials. Tubing and sometimes tanks are the largest component of the wetted surface and, therefore, it is most important for these items to be made of low-carbon material when applicable. Valves are available in low-carbon stainless-steel grades, also, and should be used in conjunction with low-carbon tubing. Specifications for low-carbon steels permit carbon content up to 0.03 weight percent as opposed to 0.08 weight percent in 304 and 316 steels. In many applications, steels with higher carbon content produce higher amounts of tritiated methane and carbide precipitates along grain boundaries in heat-affected zones (sensitization), which will make the steel more susceptible to hydrogen-induced damage.

Relieving stress in the affected heat zone is desirable for reducing surface and crevice areas. Higher-carbon steels normally contain inclusions that are troublesome for tritium environments. Choice of 316L versus 304L steel will depend on the specific application. Stems have also failed as a result of inclusions in their base metal (440 series). These stem cracks remain undetected unless examined or failure occurs.

New tubing for tritium systems should be treated by a surface reduction method (i.e., reduce roughness) inside the tubing. Some facilities successfully reduced tritiated methane formation in stainless-steel tubing by chemical or electrochemical polishing, which also benefits the quality of field welds.

As DOE moves away from tritium in gaseous form for storing and shipping to tritium in hydride form, there will be more opportunities for particulates to collect on valve stem tips and other system components. Fines confinement (currently achieved primarily through filter design) will be used eventually in conjunction with newer hydride advancements. This should be integrated with compensatory measures such as a preventive maintenance program for valves (particularly shipping container valves) to minimize this failure mechanism.

Recommendations

Enough data is available now to recommend some tritium practices, while more information is needed before recommending others. Applicability of the following recommendations should be considered in light of the required function (e.g., isolation for emergency conditions versus normal process control), environmental conditions such as pressure and temperature, stress, and consequences of failure.

Strongly Recommended Practices

1. Do not use halogenated elastomers or polymers such as Kel-F”, teflon, or viton for wetted parts in valves used for extensive tritium service. Establish specific procedures for preventive maintenance and replacement frequencies for valves containing sealing surfaces that are not tritium resistant.

2. Use packless valves (e.g., metal-bellows and metal-diaphragm valves) with stainless-steel bodies for tritium service.

3. Replace H-type Nupro valves used as barriers to contain tritium with either BG-, BW-, UG-, UW-, BN-, or DL-type Nupro valves, or equivalent, as soon as practical.

4. Establish an inspection and test program to examine all valves received from the manufacturer rather than using a statistically based acceptance inspection program.

5. Use torque limiters for manually operated valves that are cycled frequently, and include excessive torque precautions in operations procedures and training manuals.

6. Use manufacturer procedures for valve seating for both factory-supplied and field-replaced VESPEL™ stem tips.

7. Use mounting brackets or hard-mounting techniques for valves attached to tritium-bearing containers. Test valves after attachment to the container. If testing is not possible after attachment, test before attachment to the container.

Other Recommended Practices

1. Consider using copper if it is compatible with system chemistry in lieu of polymers as a stem tip material.

2. Use materials of different hardness in the stem tip and valve seat.

3. Use hemispheric stem tips for hard-metal (stellite and stainless steel) valves and for VESPEL” valves if they become available.

4. Do not use hard-metal valves with hard-landing actuators. The harder the seating materials are, the softer the landing actuators should be.

5. Consider using secondary containment-type isolation valves for portable tritium containers.

6. Use valves with inspection ports (e.g., those listed in item 3 under “Strongly Recommended Practices”) to monitor bellows integrity in conjunction with bonnet sniffer tubes for appropriate critical applications.

7. Use low-carbon stainless steel for system tubing and other large wetted surfaces. Consider low-carbon stainless-steel valves for systems that contain low-carbon stainless-steel tubing.

8. Use an acceptable passivation method such as chemical or electrochemical polishing for new stainless-steel tubing.

9. When possible, relieve system pressure from polymer stem tips that are kept in a closed position for long periods of time.

10. Minimize all field welding to the extent possible and heat sink BN valves in lieu of disassembly, welding, and reassembly.

Future Tritium-Related Technical Notices

Other tritium topics of interest and useful practices will be discussed in future Technical Notices from the Office of Nuclear Safety. Planned topics include an examination of the requirements in DOE *6430.1* A, *General Design Criteria,* for tritium facilities, with particular emphasis on the need for double and triple barriers and associated definitions of secondary and tertiary confinements. Distinctions between the terms "confinement," "containment," and "barriers to release" will be discussed.

Another topic of interest, design and operation of tritium cleanup systems, will be reviewed. For example, all glovebox and room tritium-cleanup systems currently in service are designed to convert the elemental form to oxide. Handling the oxide, whether during normal operation or after upset/accident conditions, introduces personnel exposure risks. Cleanup systems are becoming available (e.g., SAES Getters) that capture and store tritium gas within getter materials without conversion to oxide. Some factors to consider within a cost/benefit framework for employment of these type systems will be discussed.

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3. Interoffice Memo from Don 0. Coffin, Tritium Technology Associates, to J.L. Anderson, Princeton University Plasma Physics Laboratory, subject: Comments on "Valve Practices for Tritium Systems" document, DOE Safety Office, 22 April 1993.

4. DOE Occurrence Report SAN-LLNL-LLNL-1991-1002, "Tritium Release During Downsizing Activity (B-331)," 3 April 1991.

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9. Environment, Safety & Health Safety Note 91-3, U.S. Department of Energy, March 1992.

10. Memorandum from D.O. Coffin, Los Alamos National Laboratory, to J.L. Anderson, Princeton University Plasma Physics Laboratory, subject: Use of Nupro Valves (generic) in Tritium Systems, 7 August 1991.

11. Los Alamos National Laboratory memorandum, R.L. Nolen to R. Malonfant, "Response to the Office of Nuclear Safety (ONS) Request for Documentation on the Weapons Engineering Tritium Facility (WETF)," 21 December 1990.

12. Letter from Bruce Matejcik, Nupro Company, to Albuquerque Valve and Fitting Company, attention Jeff Thompson, regarding VESPEL™ stem tip valves, 16 April 1992.

Notes

a. Stellite is an alloy consisting of approximately 50 percent cobalt and 35 percent chromium.

b. John Gill, Mound Applied Technologies Plant, has developed a rule of thumb for Kel-F™ replacement because of exposure to tritium, which is: "one half atmosphere a year or one atmosphere in six months at 100 percent gas concentration." This rule is somewhat linear in terms of concentration and time.

c. Discussion with Walter Shmayda, Ontario Hydro Tritium Laboratory, 10 September 1993.

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