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To cite this article: Stefan Welte, Tobias Falke , David Hillesheimer, Joshua Kohpeiss ,
Thanh-Long Le , Simon Niemes , Florian Priester , Michael Sturm, Nancy Tuchscherer
& Tobias Weber (12 Jun 2026): Tritium Laboratory Karlsruhe Tritium Infrastructure:
Current Status and Upgrades for Future Operations, Fusion Science and Technology, DOI:
[10.1080/15361055.2026.2663234](https://doi.org/10.1080/15361055.2026.2663234)

To link to this article: <https://doi.org/10.1080/15361055.2026.2663234>



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Published online: 12 Jun 2026.



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Tritium Laboratory Karlsruhe Tritium Infrastructure: Current Status and Upgrades for Future Operations

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Received January 28, 2026

Accepted for Publication April 17, 2026

Abstract — *The Tritium Laboratory Karlsruhe (TLK) is a unique semitechnical facility dedicated to the development of tritium processing technologies encompassing analytical systems, processing methodologies, and experimental setups. Authorized to handle up to 40 g of tritium, TLK represents a central facility within the Helmholtz Association for tritium-related research and development. Since commencing operations in 1993, its proven confinement and processing philosophy has established an excellent safety record. This paper provides an overview of the current status of TLK's tritium infrastructure, summarizing operational experience, organizational frameworks, and recent technical progress. Developments addressing solutions to operational challenges, new facility interfaces, and the commissioning of a dedicated tritium isotope recovery plant are presented. An outlook on the planned tritium waste disposal facility underlines TLK's continuous commitment to innovation in tritium handling technologies.*

Keywords — *Tritium processing, tritium fuel cycle, KATRIN, windowless gaseous tritium source, Tritium Laboratory Karlsruhe.*

I. INTRODUCTION

The Tritium Laboratory Karlsruhe (TLK) was originally established in the 1980s to develop tritium handling techniques and processes for application in the fuel cycle of future fusion power plants [1,2]. The licensing procedure started in 1988, with TLK commissioned with tritium in 1994 [3,4]. Research activities have included the development of tritium confinement concepts, plasma exhaust detritiation processes, isotope separation processes, and cryogenic distillation and water detritiation systems, as well as analytical methods and components

for safe tritium processing. TLK holds a license permitting the handling of up to 40 g (1.4×10^{16} Bq) of tritium.

Originally, TLK's mission focused on developing processes for future fusion fuel cycles. In the early 2000s, this mission was extended by using the existing tritium expertise and infrastructure to build, host, and operate the KATRIN tritium neutrino experiment [5]. KATRIN aims to determine the absolute electron (anti) neutrino mass with a sensitivity better than $200 \text{ meV}/c^2$ (90% confidence level) by high-precision spectroscopy of the tritium β -spectrum near its endpoint at 18.6 keV.

The experiment relies on the continuous operation of the windowless gaseous tritium source (WGTS), which processes approximately 40 g day^{-1} of tritium with isotopic purities of at least 95% [6]. These two missions proved to be perfectly synergistic, as both required the reliable handling of substantial tritium quantities in closed loops. This provided the ideal opportunity to further develop handling technologies and gain extensive experience in continuous 24/7 tritium operations.

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TABLE 1

TLK Tritium Licence Overview in Accordance With Sec. 12 of StrlSchG, the 2019 Amendment Allowed the Use of 40 g of Tritium in the Gas Phase, Dropping the 25 g Restriction Previously Applicable

License (Sec. 12 StrlSchG)	T1/93 (Expired)	T6/07 (December 2019, Valid)
^3H (g)	10	40
^3H (Bq)	$\approx 3.5 \text{ E}15$	$\approx 1.4 \text{ E}16$
^{238}U (kg)	100	100
^{83}Rb (Bq)	–	$1.0 \text{ E}10$
^{84}Rb (Bq)	–	$5.0 \text{ E}9$

II. LICENSE

Operation of the TLK is governed by a license, issued in accordance with Section 12(1) No. 3 of the Radiation Protection Act (StrlSchG) for handling radioactive substances. This distinguishes the handling of tritium from the handling of fissile material, which must be licensed according to the German Atomic Energy Act (AtG). A detailed introduction to the TLK administrative and technical framework was given in Ref. [7], so only amendments are addressed in this paper.

Approved in 2007 and updated in 2019, the license authorizes TLK to handle up to 40 g (1.4×10^{16} Bq) of tritium, 100 kg of depleted uranium, and small amounts of $^{83}\text{Rb}/^{83}\text{Kr}$ and ^{84}Rb (see Table 1). The original license, T1/93, which was issued in 1993, limited the inventory to 10 g. The original T6/07 also imposed constraints on operation, limiting tritium handling to 25 g in the gas phase.

The 2019 amendment to T6/07 finally dropped this limit and addressed the transposition of the directive 2013/59/Euratom into German law through the StrlSchG and the StrlSchV (Radiation Protection Ordinance). This development showed not only the continuous increase in capabilities, but also the many years of mutual trust-building and experience between TLK and its regulators. The future development of experimental capabilities, particularly regarding tritium handling, will likely require the reconsideration of the current licensing limits.

A hierarchical safety and administrative framework (Fig. 1) support this license, including technical standards, risk analyses, and the Karlsruhe Institute of Technology's institutional safety rules. Building, maintaining, and operating a facility such as the TLK requires a robust administrative and technical framework defined by the tritium license. This framework establishes the safety and operational boundaries.

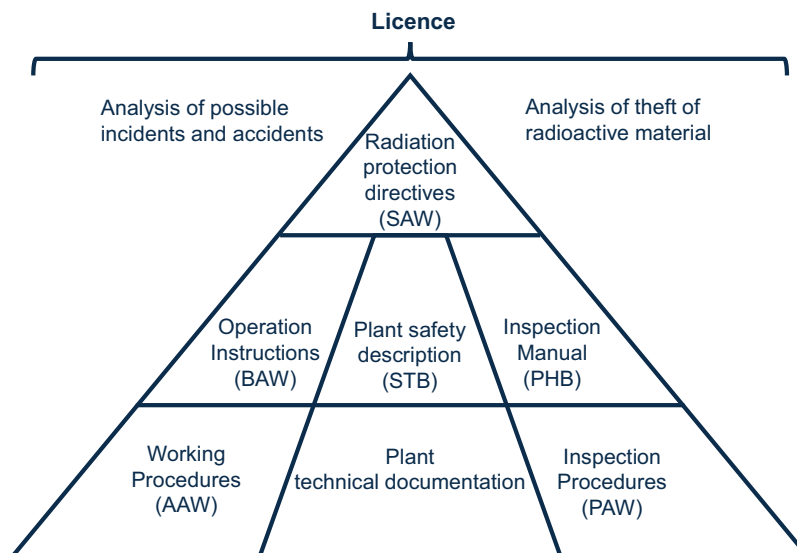


Fig. 1. Hierarchical safety and administrative framework showing the structure of the supporting documents for the TLK tritium license. It represents a top-to-bottom pyramid. The level of detail of each document increases from top to bottom.

II.A. Administrative Rules

The administrative requirements address the implementation of safety measures in the daily work, organizational structure, radiation protection, and the handling of radioactive substances, as well as standard operating and experimental procedures. They are summarized in the following sections. (Note that the abbreviations reflect the German language used, and hence do not correlate with the English translation.)

II.A.1. Radiation Protection Directives

The radiation protection directives (SAWs) govern all aspects of operations at the TLK and are mandatory in accordance with to Sec. 45 of the StrlSchV, addressing the following aspects:

1. TLK organization, key personnel, and responsibilities.
2. Radiation protection measures, the definition of supervised areas, radiation and dose monitoring, and interventions.
3. The handling of radioactive substances, experiment planning, and daily operations.
4. Admittance and visitor policies for controlled areas, the handling of alarms, emergencies, and fire protection concepts.

II.A.2. Plant Safety Descriptions

The plant safety descriptions (STBs) summarize the safety philosophy, system overviews, and risk assessments of each individual facility. The individual STBs are also used for the evaluation of compliance of new research projects or experiments with regulatory requirements.

II.A.3. Operation Instructions

The operation instructions (BAWs) cover the operational procedures, facility layout, parameters, and safe-state definitions of each individual facility.

II.A.4. Working Procedures

The working procedures (AAWs) provide stepwise workflows for normal and emergency operations.

II.A.5. Plant Technical Documentation

The plant technical documentation proves compliance with the design, safety, and quality standards, including flowcharts, component lists, certifications, and tests.

II.A.6. Inspection Manuals and Procedures

The inspection manuals (PHBs) and inspection procedures (PAWs) define the periodic inspection intervals and methods for facilities and systems.

II.B. Technical Requirements

The technical requirements define the design, construction, and quality standards that must be met to comply with the tritium license. The most critical among these are the technical terms of delivery and acceptance (TLA) for facility construction and the technical editing process for system modifications, while maintaining regulatory compliance.

II.B.1. Technical Terms of Delivery and Acceptance

The TLA outlines the design and quality standards, material and welding requirements, documentation obligations, and accreditation of suppliers. The technical requirements summarized in the TLA represent the TLK design and manufacturing standards because there is currently no common national and international tritium engineering standard.

II.B.2. Technical Editing Process

The technical editing process governs all the facility modifications, ensuring alignment with safety principles and verifying whether the changes remain covered by the existing license.

III. FACILITY: CONFINEMENT PHILOSOPHY AND TRITIUM LOOP SYSTEMS

The tritium confinement system follows a multibarrier philosophy to ensure reliable containment. Within the tritium building, the primary containment is used in the tritium processing facilities and experiments to handle high-concentration tritium mixtures in a closed loop [1–4]. This demands very high technical standards, e.g., leakage rates $< 1 \times 10^{-8}$ mbar·l·s⁻¹, a limited choice for tritium-facing materials (metallic, ceramic, glass, etc.), and

strict quality assurance (QA) requirements regulated by the TLA (II.B.1.). All the primary systems are enclosed within the second containment.

III.A. Second Containment

The second containment, which encloses the first containment, is formed by glove boxes, tritium retention systems, and related infrastructure. Although its technical requirements are less stringent (e.g., leakage rate $\leq 0.1\% \text{ vol}\cdot\text{h}^{-1}$, polymers permitted, relaxed QA), the process monitoring remains strict.

The main components of the secondary containment (Fig. 2) include the following:

1. Glove boxes.
2. Double-walled tubing connection systems.
3. Individual glove box atmosphere pressure control units.
4. Individual tritium retention systems (TRS).
5. A central tritium retention system (ZTS).

Among these, the ZTS is the most important element. It provides essential functions that enable all other secondary containment systems to operate properly by:

1. Performing final tritium retention through a double-redundant burn-and-dry system before exhaust release to the stack.

2. Supplying central subatmospheric pressure to all glove boxes via triple-redundant blowers.

3. Retaining tritium from the primary exhaust streams containing substantial unrecoverable tritium amounts.

Therefore, the ZTS is divided into a preprocessing stage for primary exhaust and a main processing stage. All key components are standardized, modular, and interchangeable.

III.B. First Containment

The first containment forms the actual tritium loop. It consists of the tritium infrastructure, including the tritium storage system (TLG), the tritium transfer system (TTS), the tritium recovery and removal system (CAPER), the isotope separation system (ISS), and the individual experiments. All of these are connected to the ZTS.

The TLK thus operates not as a simple closed loop, but as a complex, modular, and interconnected network that can be configured to serve each experiment individually while forming a closed tritium loop, as shown in Fig. 3 [4].

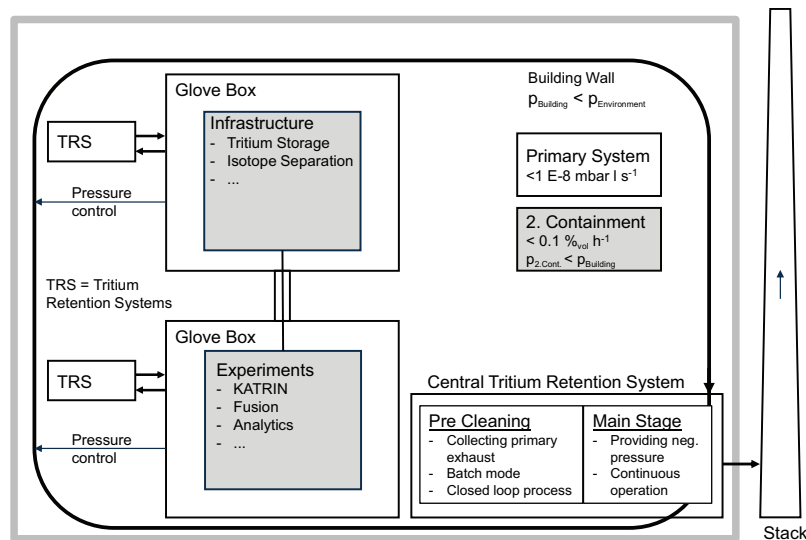


Fig. 2. Implementation of a multibarrier philosophy provides reliable tritium confinement (simplified scheme showing the main components of the second containment).

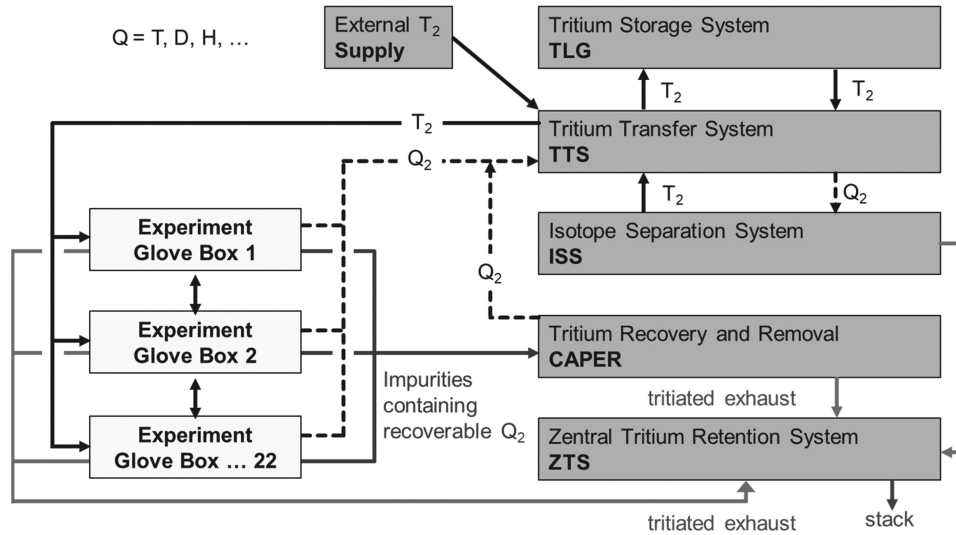


Fig. 3. Implementation of the tritium loop as a modular and interconnected network that can be configured to serve each experiment individually while forming a closed tritium loop.

III.B.1. Tritium Transfer System

The TTS provides all provisions for the external supply of tritium from transport getter beds, pVTc for determination of the gas batch amount, and internal tritium accountability. Fig. 4 shows a simplified process flow diagram of the TTS for its current function. Three volume-calibrated vessels of 108 l, 18 l, and 2 l are used for accounting, combined with temperature, pressure, and concentration measurements through laser Raman (LARA [8]) and BIXS (beta-induced X-ray spectrometry [9]) measurements.

If tritium has to be transferred, for example, from the 2 l vessel to an experiment, V-1 and V-4 are opened and

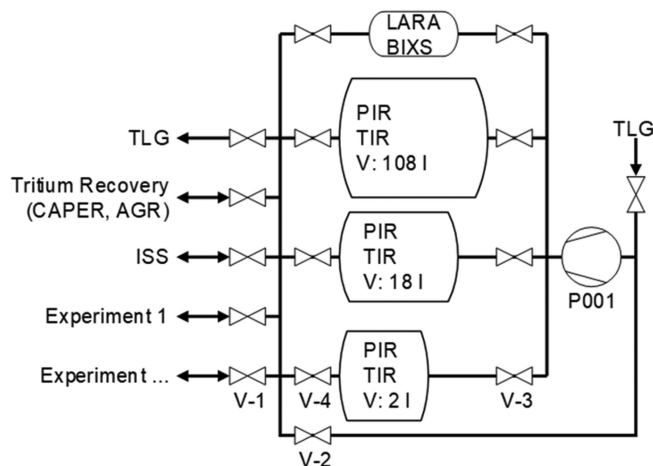


Fig. 4. Simplified process flow diagram of the TTS. Tritium batches are prepared and received in one of the calibrated buffer vessels the pressure, temperature, and composition are measured for accountability.

tritium is sent by means of the experiments pumping train. To pump tritium back to the TTS, V-1, V-2, and V-3 are opened to withdraw tritium into the respective vessel in the TTS using pump P-1. This procedure assures that tritium transfers are only performed using the accepting facility’s pumps to avoid overpressure in the transfer line. The LARA and BIXS cells are filled in the same way for analysis. Depending on the amount of tritium needed for a transfer, different vessels are used [4].

III.B.2. Tritium Storage System

The TLG stores tritium not currently used within the loop on metal getter beds. Fig. 5 shows a simplified process flow diagram of TLG for its current function. Ten getter beds are arranged to provide a closed absorption loop with the TTS through P-1, V-1, and V-3 (using absorption on B-01 as an example). Desorption is achieved by heating the getter bed to 450°C and opening V-3 using the TTS for pumping exclusively. This arrangement is provided for all 10 getter beds [4].

III.B.3. Tritium Recovery and Removal

The recovery of tritium from gas fractions that contain recoverable tritium is achieved by means of a three-stage CAPER process simplified in Fig. 6. In the first stage, a Pd/Ag membrane permeator PP001 removes most of the molecular hydrogen isotopologues (Q_2). In the second stage, catalytic liberation of Q_2 from molecules like CQ_4 in the reactor KT001 is combined with Q_2

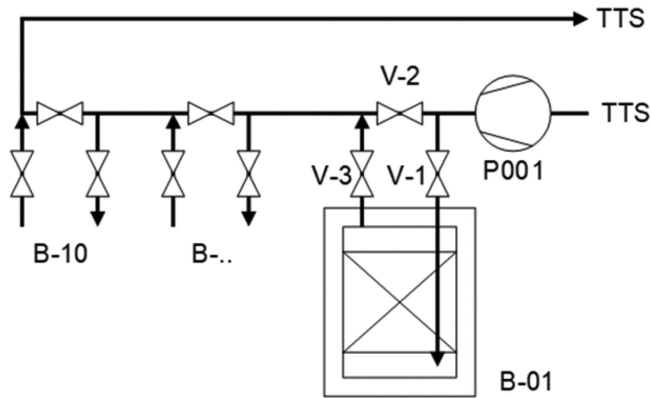


Fig. 5. Simplified process flow diagram of the TLG consisting of 10 getter beds. Tritium batches are received exclusively from the TTS and exclusively send to the TTS to guarantee reliable accountability.

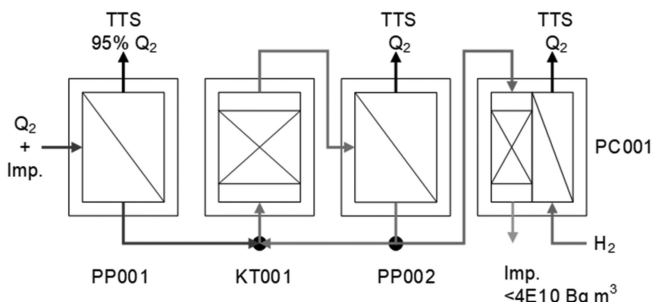


Fig. 6. Simplified process flow diagram of the three-stage CAPER process, which consists (from left to right) of a front-end permeator PP001, a catalytic reactor KT001 and permeator PP002, and a PERMCAT reactor PC001.

recovery using PP002. As a third stage, countercurrent isotopic swamping using a PERMCAT-type membrane reactor (PC001) can be used. Impurities are fed counter-current to the pure hydrogen in order to facilitate isotopic swamping in a continuous process. The Q_2 fractions of all stages are sent to the ISS after accountability in the TTS [4].

III.B.4. Isotope Separation System

The ISS enriches concentrated and strips highly diluted tritium fractions by means of displacement gas chromatography. Fig. 7 shows a simplified process diagram of the current ISS. A ~ 1.2 -mol Q_2 batch is injected into an injection coil and then pushed through the Pd/ Al_2O_3 -filled separation column, operated at ambient conditions using a H_2 eluent.

Q_2 , having a strong isotopic effect on palladium-hydride/tritide, is separated into T_2 , D_2 , and H_2 , and the different

batches are detected by means of a thermal conductivity sensor as well as an ionization chamber at the outlet of the column. Different product vessels accept the fractions from where tritium is transferred to the TTS. After a separation, the column is regenerated for 4 h at $180^\circ C$ [4,10].

III.C. Standardization and Modularity

With regard to reliability and maintainability, standardization and modularity are very important topics. In a facility operated 24/7, standardization and modularity ease maintenance and upgrades, as well as allow for interchangeability, if necessary. Having a tritium standard for manufacturing in the form of the TLA eases specifications for manufacturers. Using standard interfaces, supply limits, and process procedures, as well as process control systems and software, eases operations.

IV. OPERATION AND EXPERIENCE

Since 2018, most tritium throughput at the TLK has been processed for KATRIN operations. While KATRIN is implemented within the TLK tritium loop in the same way as other experiments, it possesses several distinctive differences:

1. The main “inner” KATRIN tritium loop is a system using internal recycling via a permeator.
2. A molecular tritium concentration of $>98\%$ is required to be fed at regular intervals from the tritium infrastructure.

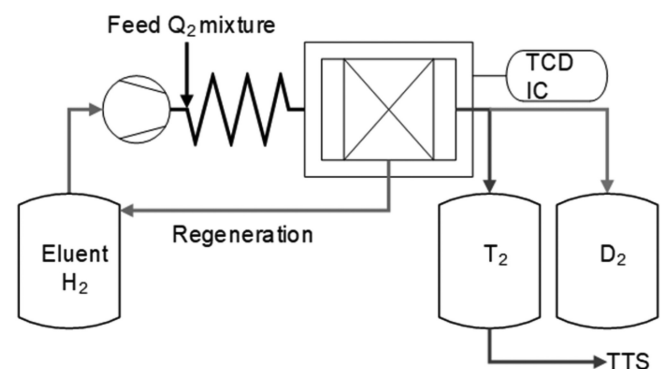


Fig. 7. Simplified process flow diagram of the ISS process. Tritium gas mixtures are pushed by the eluent through the separation column, and the pure fractions are separated based on the thermal conductivity sensor (TCD) and the ionization chamber (IC) signals in the product buffers.

3. The inner loop is typically supplied with pure tritium (>98% atomic) weekly and discharges diluted tritium twice per week.

The operation of KATRIN began in 2018 with an initial tritium ramp-up phase and has continued ever since [11]. The processing operations developed in the tritium infrastructure for KATRIN were motivated to minimize processing steps and maximize the efficiency of tritium recovery, while minimizing inventories in all systems other than the TTS. Fig. 8 shows the typical processing loop for KATRIN loop feeding and tritium withdrawal, which includes the following steps:

1. Tritium feeds from the TTS to the KATRIN loops.

2. Tritium and impurities are withdrawn in the combined operation of the TTS and CAPER, passing through the CAPER permeator directly into the TTS, leaving a minimum of retentate in CAPER.

3. LARA measurement of the permeate in the TTS. If the atomic tritium concentration is above 98%, tritium is reused for KATRIN loop feeding.

4. If the atomic tritium concentration is below 98%, tritium is transferred to the ISS.

5. Concentrate the tritium in the ISS and transfer to the TTS for LARA measurement to confirm the tritium concentration.

Periodical processing of the retentate in CAPER is performed, which also necessitates the concentration of the tritium in the ISS. Of course, such a processing order is only representative for TLK, as impurities in

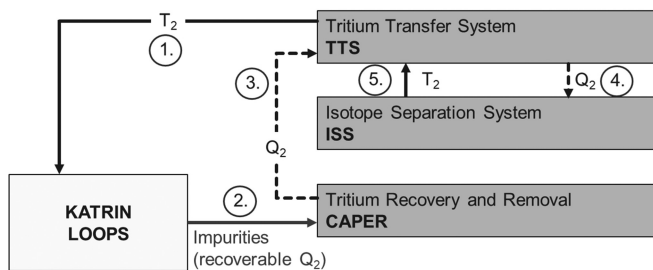


Fig. 8. Processing steps for KATRIN loop tritium supply and purification: 1. Feed with pure tritium, 2. and 3. Tritium recovery through combined processing and transfer, and 4. and 5. Optional isotope separation after analysis in the TTS.

the tritiated gas species are rather low [11], mainly due to the use of a direct recycling in the KATRIN inner loop, as described in Refs. [5,6].

Since 2018, the infrastructure throughput was approximately 3.1 kg of tritium, while the inner KATRIN loop processed 44 kg [12]. This necessitated ~1700 transfer and processing operations, 58 dedicated retentate processing operations, and 290 isotope separations producing 380 g of pure tritium. While the operations have proved reliable, nevertheless failures have had to be addressed, as reported in Ref. [13].

V. DEVELOPMENTS

Operational experience over the last few years of tritium loop operation has led to several developments and improvements. Most have been aimed at improving the availability and efficiency of operation, while solving the waste problem has become a necessity when continuously improving an old facility.

V.A. Diagnostics in the Tritium Infrastructure

Micro-LARA systems have been installed in the ISS product vessels and the TTS sampling lines, enabling rapid, in-line measurements without separate grab-sampling and improving decision-making speed, while having a minimal impact on the process installations [8].

V.B. Design, Development, and Installation of a Purpose-Built Active Gas Recovery System

As described in Sec. III, CAPER was used for the main part of the KATRIN operation for tritium recovery from KATRIN's spent tritium. CAPER was originally designed as a facility to demonstrate several concepts of plasma exhaust purification. As a result, it is a very complex and extensive facility, spread over three glove boxes. While it has always been capable of processing the KATRIN exhaust, it is very labor and maintenance intensive, and during KATRIN operation, it is fully occupied and cannot contribute to a scientific program. Therefore, the active gas recovery system (AGR) facility was integrated into the TLK tritium loop with the following goals:

1. Efficient facility to separate Q_2 from waste.
2. Simplicity and reduction in components.
3. Ease of maintenance and operation.

4. CAPER facility is free to address scientific tasks.

The AGR facility is connected to the TLK tritium loop to be used in the same way as CAPER, fulfilling the same processing function in a far smaller facility (70% reduction in components and a 85% reduction of glove box footprint). The two-stage processing function, presented in Fig. 9, is comprised of the following steps:

1. Direct recovery of Q_2 to the TTS using a Pd/Ag membrane. In this step, V-1 and V-2 are closed, forming a closed loop over PP001.

2. Catalytic liberation of Q_2 from molecules using a Ni catalyst (KT001) and recovery using a Pd/Ag permeator (PP001). In this step, V-3 is closed while V-1 and V-2 are opened, forming a closed loop over PP001 and KT001.

The key components are a Pd/Ag permeator (Fig. 10a), a catalytic reactor (Fig. 10b), and the diagnostics, which are comprised of a μ RA-Raman system, an ionization chamber, and an optical plasma gauge. The AGR was originally scheduled to be connected to the TLK tritium transfer piping during the fourth quarter of 2025 maintenance phase; however, the unavailability of CAPER due to an electrical failure forced an earlier connection to the tritium loop in order to provide tritium processing for KATRIN.

In this case, the flexible, modular, and interconnected glove box and transfer line systems allowed for a rapid connection (1 day) of the AGR to the tritium loop, enabling uninterrupted KATRIN operation despite CAPER being unavailable. The AGR has been operated

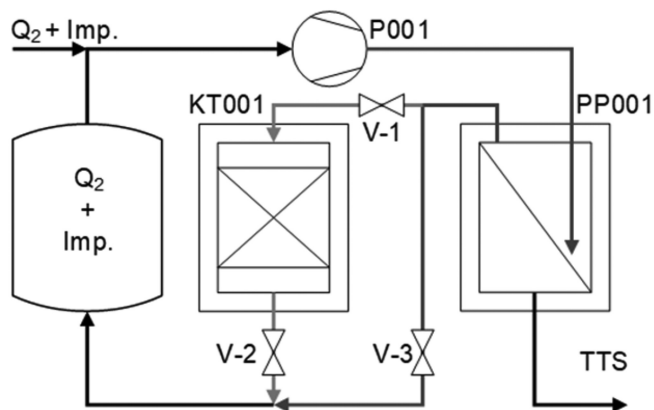


Fig. 9. Two-stage AGR process using a Pd/Ag (PP001) permeator and a Ni catalyst bed (KT001).

with tritium since May 2025. Detailed results will be published in a dedicated publication at a later stage.

V.C. Waste Handling Development

The TLK main waste challenge originated from the constant improvement of existing facilities and the installation of new experiments. Both operations produce solid noncombustible waste. Noncombustible solids from the maintenance and repair of the tritium loop components can generally be separated into three categories [14]:

1. Components that can be easily decontaminated and reused or disposed of in accordance with Sec. 33, Sec. 35, Sec. 57, Sec. 58, and Sec. 187 of the StrlSchV.

2. Material with low contamination, collected in 200-L waste barrels containing up to 3×10^9 Bq per barrel. These barrels are then disposed.

3. Tritium-contaminated noncombustible solids with an absolute activity higher than 3×10^9 Bq are currently not accepted by nuclear disposal facilities. This waste category includes all components of the first containment (tritium-facing components like tubing, valves, pump bellows, etc.). This category is the most problematic, as tritium is buried in the bulk material and needs to be released in order to achieve proper decontamination.

Different detritiation processes from the literature [15–17] were evaluated using laboratory-scale experiments under the following normalized conditions (Fig. 11):

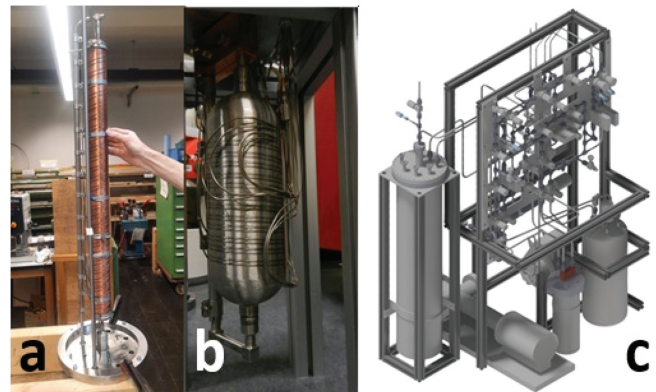


Fig. 10. (a) AGR permeator under construction, (b) Ni catalyst bed during commissioning, and (c) computer-aided design model of the facility as installed in the glove box.



Fig. 11. Picture of the experimental decontamination setup: (left side) analytical part with CuO reactor and bubblers for liquid scintillation grab samples and (right side) oven for the thermal treatment of waste samples.

1. Thermal treatment in an oxidative environment (humidified and nonhumidified air flow).
2. Thermal treatment in an inert environment (humidified and nonhumidified Ar flow).
3. Thermal treatment in a reducing environment (humidified and nonhumidified Ar/H₂ flow).
4. Melting using H₂ and Ar purge (due to experimental limitations, a full melting of a sample could not be achieved).

The goal was to identify the simplest processing option suitable for implementation in the TLK tritium loop without creating secondary waste. Employing a tube furnace at ~1000°C, the total specific activity release of several tube samples taken from a decommissioned primary system was measured by liquid scintillation using air, Ar, and Ar-H₂ as a purge gas, with both dry and humidified conditions. The samples were always comparable and taken from the same piece of tubing. The impact of the purge gas on the tritium

release was not observable within the accuracy of the measuring system. The experimental results are shown in Fig. 12.

The different detritiation processes were evaluated according to a multicriteria analysis, considering the requirement to operate within the TLK tritium license framework. Both the experimental results and the specific facility conditions at TLK were assessed, using the following criteria [18]:

1. Efficiency.
2. Risk and safe confinement.
3. Secondary waste generation.
4. Cost and availability.
5. Complexity and maturity.

Based on the results gathered, the TLK designed a detritiation process to accommodate large parts with approximately a 40-cm diameter and 50-cm height (like vacuum vessels up to DN250CF) using a nonhumidified inert gas (Ar) at a temperature of 1000°C to 1500°C, as the most cost-effective and safe option for processing tritiated waste at the TLK. Using this process, highly

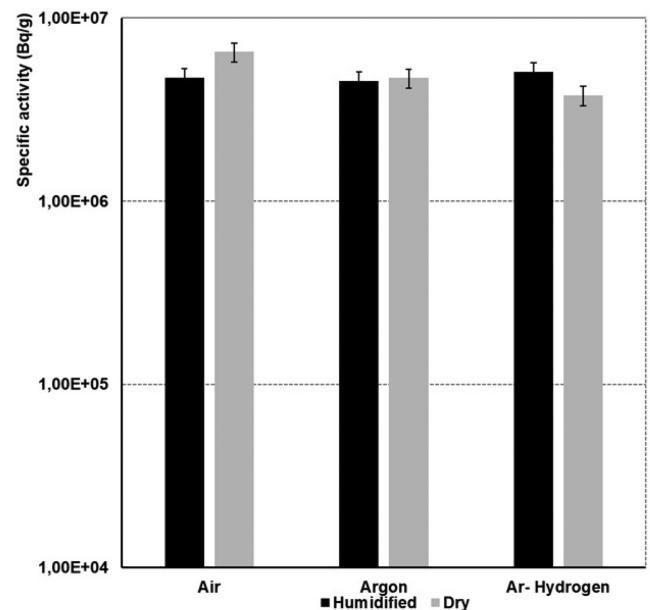


Fig. 12. Total specific activity release for air, Ar, and Ar-H₂, in both dry and humidified conditions, at 1050°C. The differences were not noticeable within the total measurement inaccuracy. The error bars indicate a ±12% error.

contaminated components can be processed to meet final disposal facility requirements while having a minimal impact on the ZTS and the tritium recovery and removal systems.

The melting for tritium extraction facility, which was designed to be fully compliant with the TLK tritium license, is comprised of a specially designed glove box, a TRS, and a primary system. The primary system consists of a tritium-compatible induction furnace designed by TLK, auxiliary piping, pumping, and a fully integrated interface to the TLK tritium loop (isotope recovery and the ZTS). The details for the process development, design, construction, and commissioning will be presented in a dedicated publication at a later stage.

This interface will allow the recovery of recoverable amounts of tritium through the tritium recovery and removal systems (Secs. III.B.3. and V.B.), while non-recoverable tritium traces will be retained in the ZTS (Sec. III.A.) as primary exhaust.

The current status is as follows:

1. The glove box, including an in-box crane for heavy parts and a preparation box for dismantling and conditioning, has been set up (Fig. 13).
2. TRS manufacturing is nearing completion.
3. A furnace for inactive testing is in operation; preliminary tritium tests are in preparation (Fig. 14).
4. The process design has been finalized.
5. A large induction-heated vacuum furnace is under design.

V.D. Overview of Developments of Experiments for the Next Decade of the TLK

Beginning with the melting for tritium extraction project, the TLK will continue developing advanced methods for decontaminating materials exposed to tritium, including both surface [Tritium Exposure and Decontamination (TED) [19] and Tritium Adsorption Desorption Experiment (TRIADE) projects] and bulk treatments.

With the growing fusion industry, understanding the physical properties of solid tritium has become increasingly important. The TLK is launching projects to investigate liquid and solid tritium in macroscopic quantities (grams). The commissioning of the Tritium Absorption Infra Red Spectroscopy (TAPIR2) facility with tritium is planned for the foreseeable future [20,21]. Furthermore,



Fig. 13. Glove box, including an in-box crane for heavy parts and a preparation box for dismantling and conditioning.

in the Tritium Phasespace Navigation for Inertial Fusion Target Production (TriPan) project, solid $H_2/D_2/T_2$ crystals can be produced and characterized in situ using optical techniques such as Fourier-transform infrared

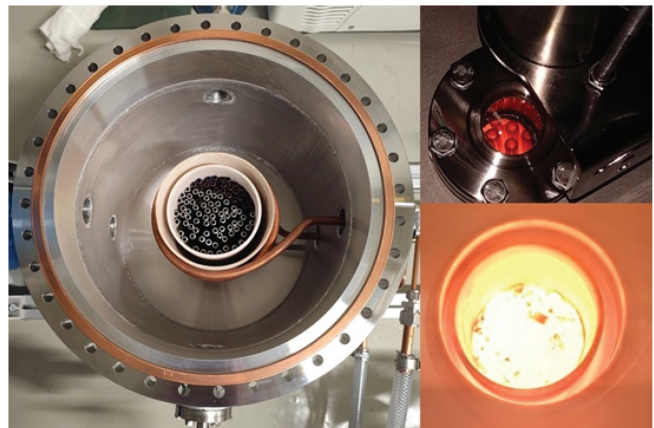


Fig. 14. Melting experiment with 6×1 -mm process tubing, typically used in tritium applications.

and Raman spectroscopy. A further step involves studying the production and filling procedures for solid cryogenic pellets used in fusion applications.

Improving energy-efficient tritium extraction from large purge gas streams, as encountered in solid ceramic breeder blankets, is another focus area that will be addressed in the Tritium Extraction Experiment (TriTEEx) project.

To ensure the safe operation of future fusion power plants, mitigation of tritium permeation needs to be addressed. The TLK, therefore, is testing various permeation barrier concepts [22].

In another field of applied tritium research, the TLK is contributing to the KATRIN experiment, which has successfully completed its tritium-neutrino campaigns. To further improve the results, the tritium source will be modified to use atomic rather than molecular tritium. The TLK conducts fundamental research to develop high-luminosity atomic tritium sources for future KATRIN upgrades and similar advanced experiments [23].

VI. CONCLUSIONS: LESSONS LEARNED AND SUMMARY

Based on the last 7 years of KATRIN operation, the following main conclusions can be drawn. The comprehensive concepts for administration and operation at the TLK have provided a solid and flexible basis for scientific experiments with tritium. The standardization and modularity paid off by providing safety, efficiency, and flexibility. Furthermore, the barrier concept and the TLK tritium loop concept have been validated many times, providing safety, efficiency, and flexibility.

The new in-line analytical systems for fast decision making have led to more efficient processing, enabling rapid decision making during processing. With regard to the use of the CAPER facility for isotope recovery, the results have been mixed. While it fulfilled its task, using a science-driven facility as a service facility for large-scale processing operations is suboptimal; a specialized solution was found to be more efficient, less complicated and labor intensive, and more able to free facility space for scientific experiments, as space in a tritium handling area, especially in glove boxes is very valuable.

Finally, a specialized solution for solid waste processing is needed. Addressing the need for dedicated tritium recovery from exhaust has been achieved, while a facility for waste treatment is under development and construction.

Acknowledgments

The authors would like to thank all their colleagues at the TLK for their support during this work.

Author Contributions

CRedit: **Stefan Welte**: Investigation, Project administration, Supervision; **Tobias Falke**: Investigation; **David Hillesheimer**: Investigation; **Joshua Kohpeiss**: Investigation; **Thanh-Long Le**: Investigation; **Simon Niemes**: Investigation; **Florian Priester**: Investigation; **Michael Sturm**: Investigation; **Nancy Tuchscherer**: Investigation; **Tobias Weber**: Investigation.

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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