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FUSION SAFETY:

A different set of variables

By Paul Humrickhouse

Fusion energy beckons with the prospect of increased safety, reduced radiological hazards, no long-lived radioactive waste, and a virtually inexhaustible fuel supply. Fusion reactors do, however, use and produce some radioactive materials, and mitigating the effects of those materials is a necessary part of fusion reactor design. Fusion safety issues are both like and unlike those encountered in fission, and ongoing research and development supported by the Department of Energy is investigating the critical issues of tritium and radionuclide transport in fusion reactor materials and systems.

Experiments and modeling carried out at Idaho National Laboratory's Safety and Tritium Applied Research (STAR) facility are key components of that research.

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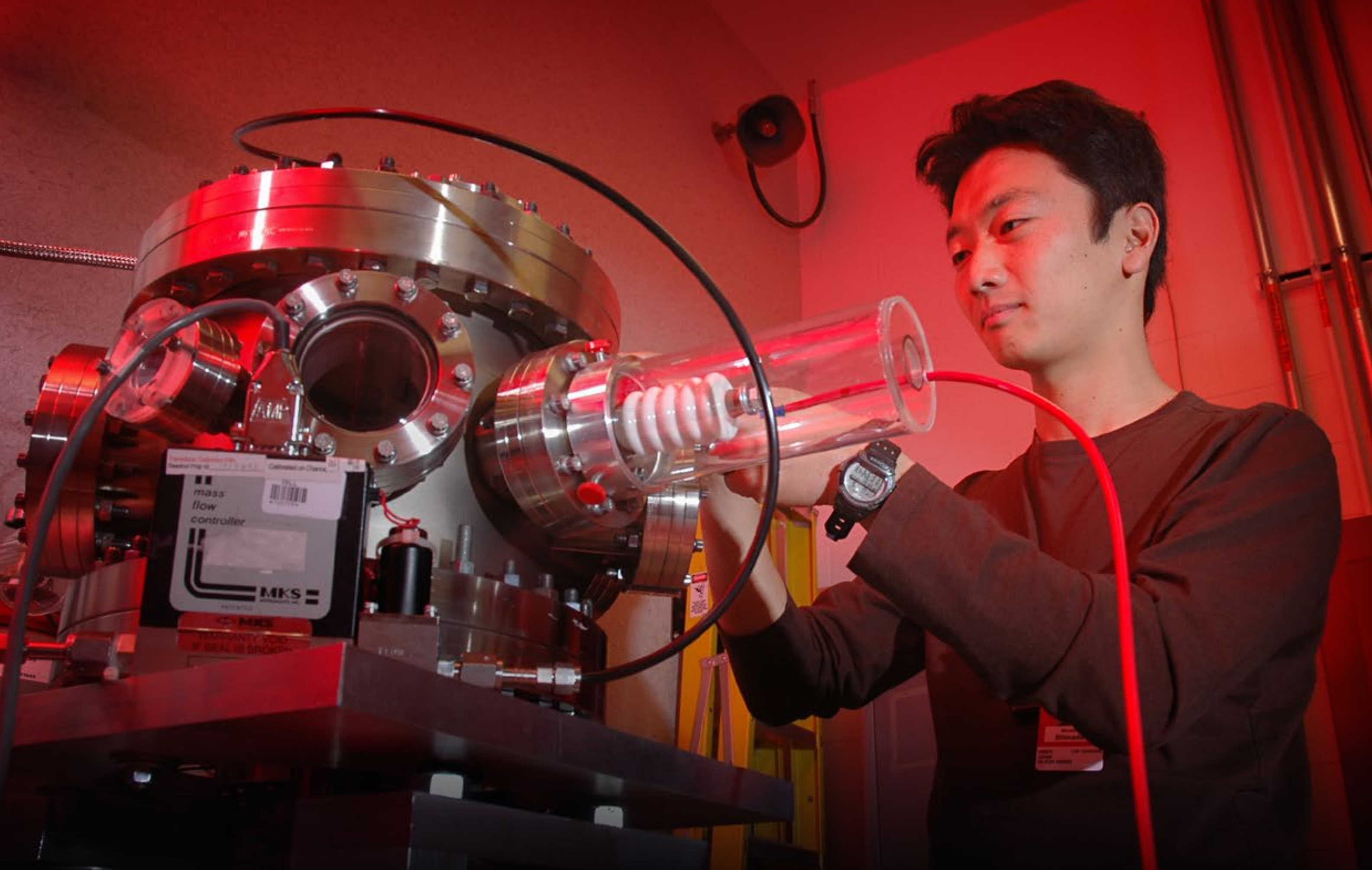
Rob Kolasinski of Sandia National Laboratories working on the Tritium Plasma Experiment.



Above: STAR experimental lead Masa Shimada with a Langmuir probe test chamber.

The D-T fuel cycle

The radiological hazards associated with fusion devices are closely linked to the selected fuel cycle. The deuterium-tritium (D-T) fuel cycle is the choice of most next-step devices worldwide. This fusion reaction combines deuterium and tritium to yield helium and a neutron and has a much larger cross section than other fusion reactions at temperatures approaching 150 million °C, achievable in magnetic confinement devices.

Tritium is radioactive and has no natural supply, so after initial startup, a fusion reactor must produce its own tritium in a lithium breeding blanket. Fusion neutrons react with lithium to yield helium and tritium, and to achieve a tritium breeding ratio greater than 1, the addition of a neutron multiplier of either lead or beryllium is typically necessary to offset the loss of neutrons by absorption in surrounding structures and coolants.

While the two-stage fusion/breeding reaction consumes deuterium and lithium and directly produces only stable helium, the neutrons inherent to the process lead to the creation of significant inventories of radioactive materials through neutron activation in the surrounding structures and coolants. The extent of the radiological hazard posed by that activation, as well as the decay heat and the nature and quantity of the waste produced, depend entirely on the materials used in the reactor and the extent to which those materials can become activated.

Controlling neutron activation effects

An immediate result of neutron activation is the production of decay heat after reactor shutdown. Many fusion reactor designs being pursued worldwide envision the use of reduced-activation ferritic/martensitic (RAFM) steel as the primary structural material in the blanket and other structures. While an exact determination of decay heat depends on the details of each design, these reactors can reduce decay heat production by half or more compared to a fission reactor.

Decay heat is also distributed throughout the blanket and the vessel surrounding the toroidal plasma, which, at several meters or more in major radius, represents a much larger volume than the fuel pins in a fission reactor core. The resultant decay heat density is therefore lower, making decay heat a more manageable problem in fusion reactors than in fission reactors. Nevertheless, ensuring that this can be adequately managed during scenarios such as loss-of-flow or loss-of-coolant accidents is an important safety objective in the design of a fusion reactor. Demonstrating passive decay heat management has always been an objective of U.S. fusion reactor design studies, and a preference for passive decay heat removal is codified in the DOE's fusion safety standards.

With effective management of decay heat, most of the radionuclide inventory of a fusion reactor is safely immobilized in solid structures. While radionuclides present in coolants could potentially be mobilized, most fusion coolants will have inherently low activation. Candidates include helium, lead-lithium eutectic (PbLi), and FLiBe (a salt comprising lithium fluoride and beryllium fluoride). PbLi has long been a focus of U.S. blanket designs, and its activation products of principal concern are mercury-203 and polonium-210. The latter is produced through a two-step activation involving bismuth-209, and active control of the bismuth concentration has been proposed as a means of limiting Po-210 production.

One of the most promising aspects of fusion is its potential to avoid the generation of long-lived radioactive waste. This can be achieved through appropriate engineering of structural materials and coolants to eliminate any materials that can activate to long-lived isotopes. RAFM steel is the product of just such an engineering effort; it is a modified grade 91 steel, without molybdenum and niobium. Using such low-activation materials in fusion reactors results in predominantly Class C low-level waste, which does not require deep geologic disposal, and which by definition presents minimal hazard, even to potential inhabitants of the disposal site 500 years in the future. The use of these materials in future fusion reactors will ensure that the devices operate safely and are also environmentally benign, leaving no significant waste legacy.

DOE fusion safety standards

The DOE's standards for fusion safety, DOE-STD-6002-96, *Safety of Magnetic Fusion Facilities: Requirements*, and DOE-STD-6003-96, *Safety of Magnetic Fusion Facilities: Guidance*, were published in 1996 and are now being revised. The standards include the following requirements:

☑ The public and the environment shall be protected such that no individual bears significant additional risk to health and safety from the operation of those facilities above the risks to which members of the general population are normally exposed.

☑ Fusion facility workers shall be protected such that the risks to which they are exposed at a fusion facility are no greater than those to which they would be exposed at a comparable industrial facility.

☑ Risks both to the public and to workers shall be maintained as low as reasonably achievable (ALARA).

☑ The need for an off-site evacuation plan shall be avoided.

☑ Wastes, especially high-level radioactive wastes, shall be minimized.

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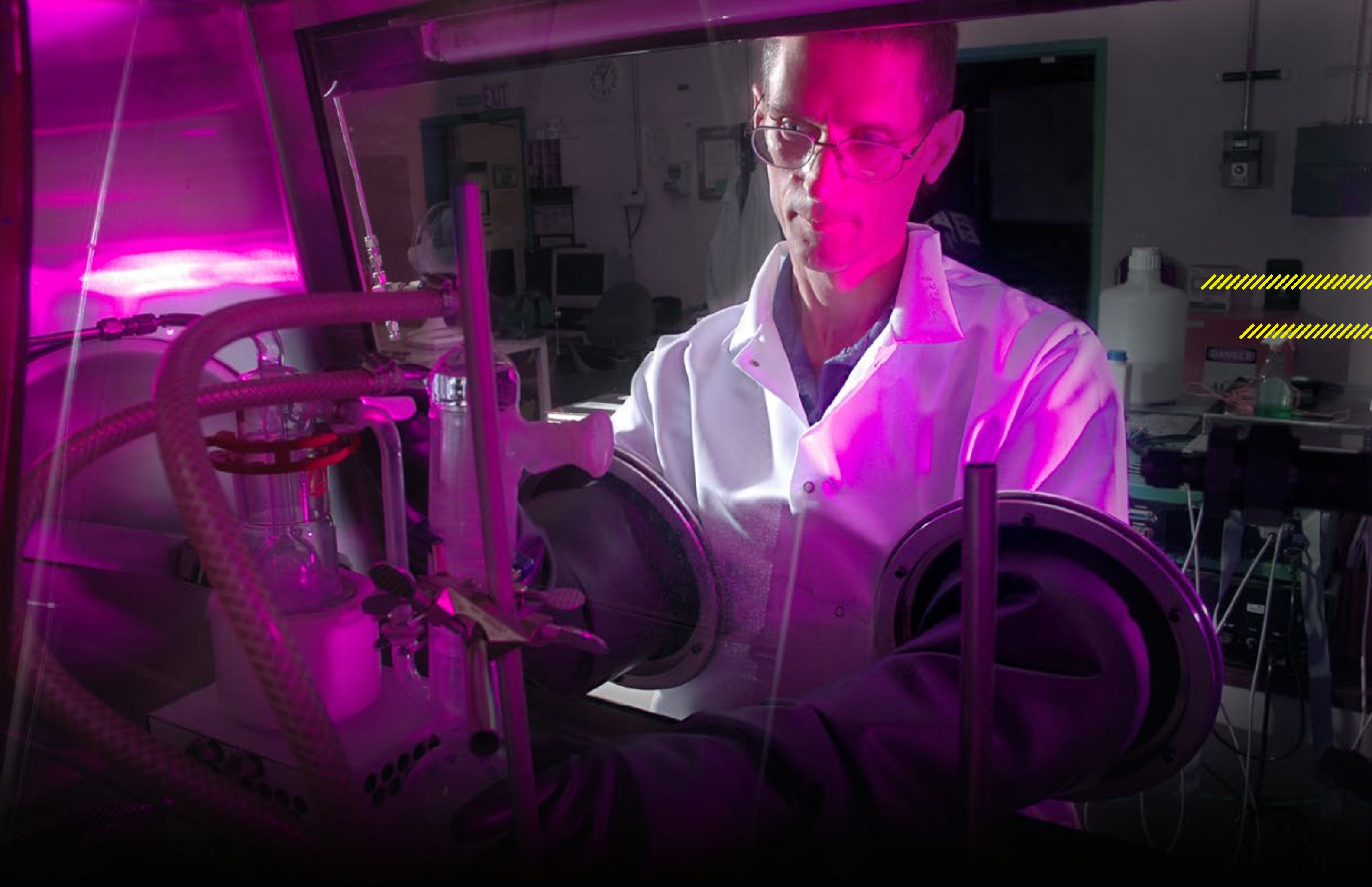


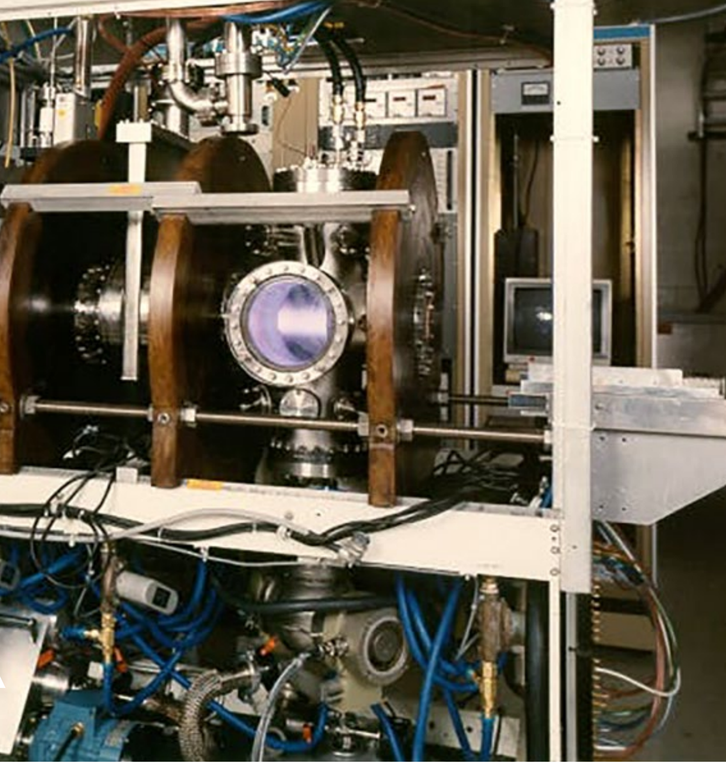
Stored energies

The initiating events that could lead to a potential radionuclide release are somewhat different in fusion than in fission reactors. An important feature of the fusion reactor is that because it is actively fueled and is not reliant on a chain reaction, there is no analogue of the reactivity transient in a fission reactor. Fusion does possess some unique stored energies in the plasma itself and especially in the superconducting magnets, and these must be managed.

A tokamak plasma can become unstable and undergo a disruption, rapidly imparting its energy to plasma-facing surfaces, potentially damaging those surfaces and leading to coolant leaks. Disruption mitigation is needed for future tokamak designs and is an active area of research. Similarly, events such as a superconducting magnet quench—when a portion of the superconducting coils controlling the plasma abruptly enters a normal, resistive state—must be mitigated to avoid damage to the magnets and surrounding structures. Other more familiar challenges include potential overpressure from coolants near phase change and the avoidance of exothermic reactions of air or water with metals such as pure lithium or beryllium, which are used in some fusion reactor designs.

Above: Bob Pawelko working on a beryllium-steam reactivity experiment.

Right: The Tritium Plasma Experiment (TPE).
Below: A target exposed to plasma in the TPE.



A closer look at tritium

Other radioactive inventories that could potentially mobilize are tritium and radioactive dust. Tritium is radioactive and undergoes a weak (18.6 keV) beta decay with a 12.3-year half-life. This is insufficiently energetic to pose an external exposure hazard. But, as an isotope of hydrogen, tritium is readily incorporated into water and organic molecules and therefore presents an exposure risk when inhaled or ingested in this form.

A D-T fusion reactor will burn tritium at a rate of 55.6 kg/GWyr, and therefore must breed it at a slightly higher rate. This rate of production is about a million times that of a light-water reactor and about a thousand times that of a heavy-water–moderated CANDU or fluoride salt–cooled reactor. Because only about 1 percent of tritium injected into the plasma is burned, with the remainder exiting as exhaust for reprocessing and reuse as fuel, the tritium throughput in the fueling and exhaust loop must be one hundred times higher still.

Concerns arising from such high tritium throughputs include the accumulation of large inventories in the reactor and its ancillary systems, which could be released in the event of confinement breaches or temperature increases during an off-normal event, and permeation through metal structures during normal operation, which increases exponentially with temperature. Design mitigations to limit permeation (such as permeation barriers and efficient extraction systems) and minimize tritium inventory are significant design challenges for future fusion reactors.

Dust matters

Dust is created in fusion systems by interactions of the plasma with solid surfaces on the first wall and divertor, including sputtering and nucleation, arcing, and flaking of surface imperfections or co-deposited layers. Dust comes to rest on the walls but may potentially be resuspended and mobilized in the event of a loss of vacuum involving air or coolant ingress. Significant efforts worldwide have been devoted to characterizing the size distribution, composition, and morphology of dust in tokamaks. Particles typically have an average diameter on the order of a few microns, but with a wide distribution of sizes and very different shapes—from spherical to irregular flakes and agglomerates—owing to the variety of dust generation mechanisms.

Dust transport models based on these characterizations assess the extent of mobilization and transport in accident scenarios in which dust might contribute to a radionuclide release or participate in chemical reactions. The amount of dust production in future reactors is uncertain, and in the near term, the approach for facilities such as ITER has been to fix a conservative administrative limit on the amount of dust in the vessel, monitor its accumulation, and clean it up as necessary.

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The STAR facility

At INL's STAR facility, a DOE less-than-Hazard-Category-3 nuclear facility, neutron-irradiated materials are exposed to tritium plasma in the Tritium Plasma Experiment in order to understand how tritium is retained at trap sites created by neutron damage. Other test stands are devoted to the measurement of deuterium and tritium permeation in fusion materials and the development of permeable membranes for efficient tritium extraction from PbLi, as well as plasma exhaust and separation, technologies that can significantly reduce unwanted tritium permeation and inventories.

Other work is devoted to the collection and characterization of tokamak dust and to experiments involving beryllium, made challenging by its toxicity. Prior beryllium-related studies have included the investigation of tritium transport in FLiBe and oxidation studies of beryllium in various forms, including dust. Information obtained at STAR informs tritium, dust, and general radionuclide transport models in MELCOR/TMAP (Tritium Migration Analysis Program), a version of the MELCOR code customized by INL for fusion applications, including fusion-relevant breeder and coolant materials and tritium transport models. This "fusion" version of MELCOR is used in ITER licensing and in design studies in the United States and worldwide.

Top: Source anode in an x-ray photoelectron spectroscopy (XPS) system used to characterize surface chemistry of fusion materials. **Bottom:** Bob Pawelko working with beryllium dust.

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