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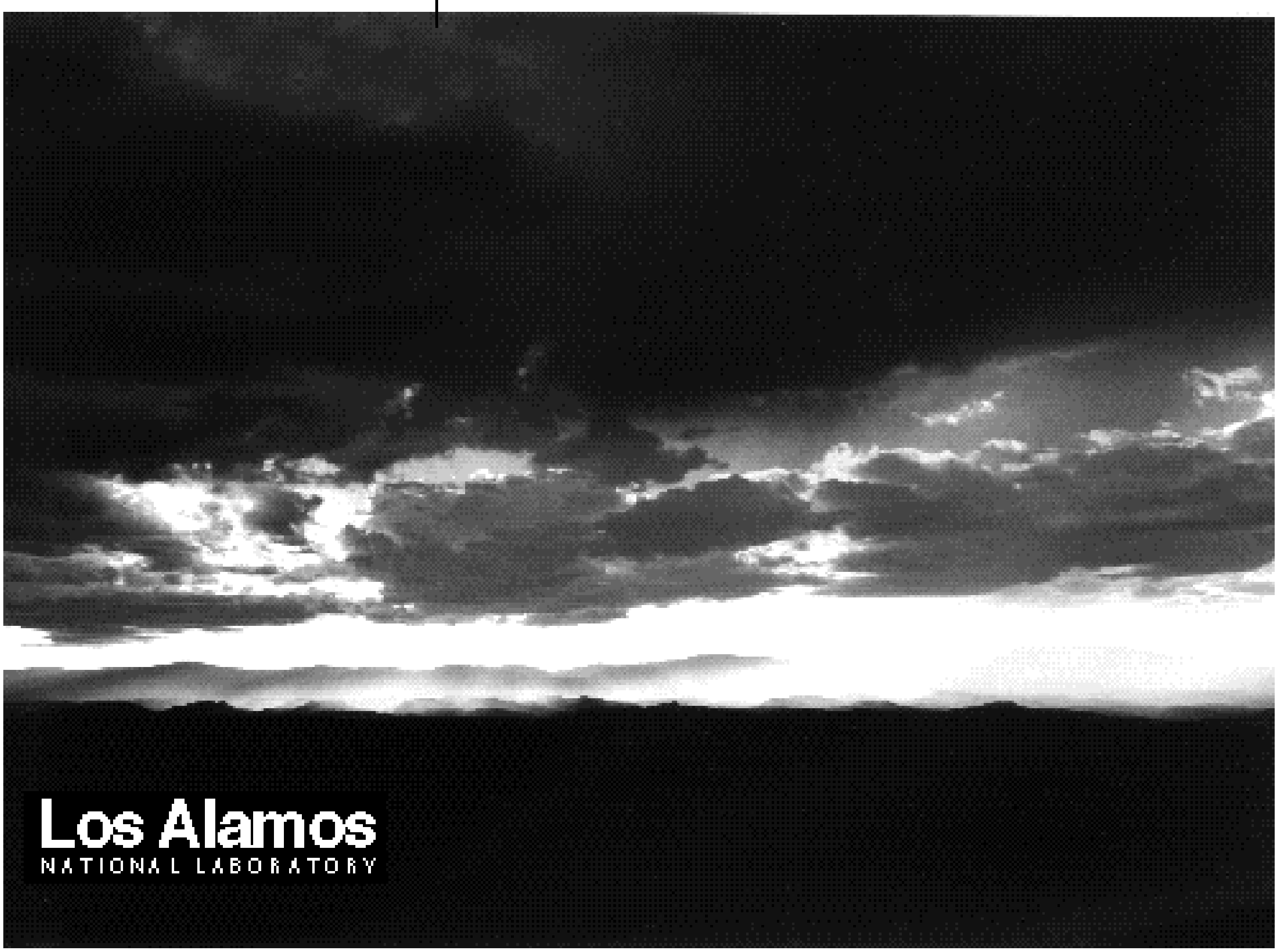

ACCELERATOR PRODUCTION OF TRITIUM SAFETY PROGRAM

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ABSTRACT

The Department of Energy (DOE) has selected the Accelerator Production of Tritium (APT) as one of the methods in a dual track strategy for meeting the nation's continuing need for tritium. One of the advantages of APT is its safety.

In APT, safety is integrated in the design process through the development of safety requirements. In executing the APT safety program, the process begins with a detailed assessment of the specific hazards, including the type and magnitude. Based on these hazards, preventive and mitigative features are incorporated in the design. The extent to which the design features are required to prevent and mitigate accidents to protect the workers, the public, and the environment determines the design requirements for the specific features.

After the hazards are identified and the design requirements are established, accident analyses are performed to demonstrate that the systems will perform their intended accident mitigation functions.

This paper reports on the APT safety methodology, the identification of hazards, the preventive and mitigative features of the APT, and the progress with the preliminary accident analyses.

I. APT OVERALL SAFETY PHILOSOPHY

As the nation's tritium source, the design and safety requirements for Accelerator Production of Tritium (APT) are associated with providing a safe and reliable facility that meet the most stringent safety, reliability, availability, maintainability, constructability, inspectability, and operability requirements. The APT safety philosophy is based on safety by design, with safety providing design input from the earliest stages of conceptual design. These requirements provide a substantial basis on which to develop the safety goals and provide a significant margin of safety to protect the health and safety of the public, the workers, and the environment.

The appropriate level of safety for APT is assured through the process of implementing the Department of Energy (DOE) orders that regulate the safety requirements. The principal order is DOE-ORD-420.1, "Facility Safety." This order covers four areas: nuclear safety, fire protection, nuclear criticality safety (which is not applicable to APT), and natural-phenomena hazards mitigation.

The safety requirements are guided by hazards and safety analyses that identify and establish the safety functions of Structures, Systems, and Components (SSCs) for the facility. Safety analyses consider facility postulated events initiated by human errors, equipment failures, natural phenomena, and external man-made induced hazards. The safety analysis is initiated at the earliest stage in conceptual design so that the performance and functional requirements for the SSCs important to safety are specified in the earliest phases of the design. The safety case is developed based on the applicable requirements stated in DOE Order 5480.25, "Safety of Accelerator Facilities," and DOE Order 5480.23, "Nuclear Safety Analysis Reports."

APT is designed with the objective of providing multiple layers of protection to prevent or mitigate the release of radioactive materials to the environment. Defense in-depth considerations for APT include: siting, minimization of material at risk, the use of conservative design margins, and quality assurance; the use of successive physical barriers for protection against the release of radioactivity; the provision of multiple means to ensure critical safety functions; the use of equipment and administrative controls that restrict deviations from normal operations and provide for recovery from accidents to achieve a safe condition; means to monitor accident releases required for emergency responses; and the provision of emergency plans for minimizing the effects of an accident.

II. APT SAFETY METHODOLOGY

The safety methodology is described in this section.

A. Facility Safety

As stated, APT will be governed by applicable DOE rules, orders, and standards. To implement this, the APT program will develop a comprehensive set of general requirements that includes environment, safety, and health (ES&H) standards and requirements, along with applicable design and operational requirements. These requirements will be captured and controlled in the Facility Design Description (FDD) document. Lower tier system specific safety requirements will be developed in the System Design Descriptions (SDDs).

As a new facility, APT has the opportunity not only to comply with regulatory standards but to design the hazards out of the facility by understanding the inherent hazards and modifying the design to eliminate or minimize the potential hazards for APT. APT has adopted this strategy where it is feasible.

The APT project will demonstrate compliance with FDD safety requirements through preparation and control of a Safety Analysis Report (SAR). The Preliminary Safety Analysis Report (PSAR) will be prepared and approved before the procurement of materials and components, and the start of construction of APT. A Final Safety Analysis Report (FSAR) that reflects design modifications during construction and contains additional information about facility operations not contained in the PSAR will be prepared and approved before the APT is operated.

The PSAR and FSAR will be developed following the hazard-based approach delineated in DOE-STD-3009-94 “Preparation Guide for US DOE Non-Reactor Nuclear Facility Safety Analysis Reports” as it applies to new facilities. This methodology provides a systematic approach for developing safety documentation that is consistent with the level of hazard and consists of the following steps:

Hazard Identification includes identification of all hazardous energy sources, radiological hazards, nonradiological toxic hazardous materials, and possible initiators for release of hazards (such as natural phenomena hazards or external events) that if released could pose a hazard to facility operations, to the environment, workers, or to the public.

Hazard Analysis includes an evaluation of the identified hazards relative to possible events and their causes. Available mitigative and preventive features are identified for each event. The consequences of each event are qualitatively evaluated and the events are grouped based on hazard level and potential event frequency. This grouping permits selection of safety significant functions and permits safety analysis to focus on the most critical (safety class) events.

Functional Classification includes identification of structures, systems, and components that provide the required worker safety and defense-in-depth safety significant functions. Additionally, it provides preliminary selection of the structures, systems, and components that could provide a required safety class function.

Accident Analysis includes development of event scenarios and analysis of specific events to verify that a safety class function is required and that the structures, systems, and components selected to prevent or mitigate the event can meet the safety class criteria.

Final Functional Classification includes final selection of structures, systems, and components credited in the safety analysis that provide the required safety class functions.

Technical Safety Requirement ensures that these safety class and safety significant functions are maintained, protecting the safety envelop of the facility.

Safety Analysis Report provides formal documentation of the safety case for the facility.

B. Worker Safety

DOE-STD-3009-94 emphasizes worker safety and gives specific design and operational attention to worker safety through administrative controls and classification as Safety Significant. SSCs and administrative controls that are identified to perform a safety significant function are described in the safety analysis report and are included in the technical safety requirements.

Worker safety is implemented through several programs. DOE implements industrial safety through compliance with Occupational Safety and Health Act (OSHA) regulations. Additionally, DOE has an As-Low-As-Reasonably-Achievable (ALARA) radiation protection program that includes requirements to minimize exposure of workers to both radiological and nonradiological toxic hazards. The applicable OSHA regulations and ALARA program are integrated within the APT processes and procedures.

III. APT SAFETY

The major safety considerations for the accelerator, the target/blanket, the tritium separation facility, and the balance of plant are summarized below. The various classes of accidents that will be evaluated for APT are presented in Table 1.

A. Accelerator

The primary hazard associated with the accelerator is localized ionizing and nonionizing radiation produced by normal beam operation or accidental beam impingement on accelerator surfaces (i.e., beam spill). These are hazards for the workers but the hazards for the public are negligible. It is important to note that an inherent feature of an accelerator is that particle acceleration cannot take place except in a vacuum. In an intense beam spill, the high-energy beam will melt the beam tube and terminate the accelerator operation. To supplement this inherent safety feature of the accelerator, worker protection is provided by a redundant and diverse combination of shielding, radiation monitoring systems access interlocks, and beam shutdown system.

Passive shielding is provided around the accelerator tunnel to limit the exposure of workers during all normal beam operations and postulated accident conditions. Because of its worker safety and defense-in-depth characteristics, the accelerator shielding is classified as a safety significant structure.

In addition to the shielding, radiation monitors located throughout the beam tunnel detect the effects of beam spill (or other high radiation initiating events) and rapidly shut down the beam. Beam shutdown is triggered not only by abnormal radiation levels in the beam tunnel, but also by target/blanket parameters. The radiation monitoring systems are also classified as safety significant systems.

Personnel protection is also provided by an interlocked access control system that prevents beam operation if personnel attempt to enter accelerator areas where ionizing radiation, radio frequency (RF) radiation, or other hazardous conditions exist. The access control system is supplemented by the accelerator confinement system, which monitors and controls the beam tunnel atmosphere. Both the personnel access control system and the accelerator confinement system are classified as safety significant systems.

Other hazards posed by the accelerator are consistent with standard industrial hazards. For example, RF fields produced by the accelerator and its associated systems are controlled through a combination of shielding, monitoring systems, shutdown systems, and personnel access control systems. Cryogenic helium is used to cool the high-energy portion of the accelerator. This introduces hazards that are controlled by industrial standards.

B. Target/Blanket

The principal hazard in the target/blanket systems is the inventory of the radionuclides that result from the spallation of the protons in the tungsten, and activation of materials by the neutrons. Based on the design features included in the target/blanket, the potential for releasing a significant fraction of the radionuclides within these systems is very small. While coolant covers the target/blanket modules either within the normal cooling systems or in the cavity vessel, the components will be cooled sufficiently so that the risk to the public from these hazards is negligible. Some of the design features contributing to this overall safety are described below:

APT has no fissionable material, and the target/blanket modules inherently have low decay heat. Decay heat from the target/blanket is about 1% of full power at the time of beam shutdown. Additionally, APT has no delayed neutrons after the beam is shut down and therefore the rate of power decrease after a beam shutdown is very rapid.

The APT gaseous feed stock allows for continuous processing of tritium resulting in low, hazardous material inventory at risk; processing waste is minimized.

The target/blanket system has multiple radionuclide barriers for both worker and public protection. These include the Inconel cladding of the tungsten rods, aluminum cladding around the lead blanket regions, primary coolant systems, the secondary and tertiary cooling systems preventing contaminated cooling leaks to the environment, a cavity vessel, and the confinement systems.

The design includes multiple means to perform important safety functions. Redundant and diverse means to shut down the beam are provided. Redundant and diverse means to provide cooling are provided (primary cooling systems, redundant residual heat-removal systems, a cavity flood system, a cavity flood cooling system, and a cavity flood boiloff capability).

In a loss-of-coolant accident (LOCA), the accelerator beam and primary coolant pumps are shut down with a safety class system that is diverse and redundant. This system includes fail-safe features that ensure that on loss of signal from the monitoring system, the system will result in a beam shutdown.

Analysis shows that in the accident transient, the power always decreases faster than flow, so that the target/blanket is overcooled in the initial phase of an accident. The low decay heat and rapid accelerator beam shutoff greatly facilitate the prevention or mitigation of the consequences of potential accidents.

The tungsten neutron source module has a safety advantage because of its high temperature capability. The tungsten rods will be clad with Inconel to minimize corrosion and prevent vaporization of the tungsten rods during accident conditions. It is designed with a large thermal hydraulic margin.

All of the coolant loops are at low pressure (less than 1.73 MPa, or 250 psia) and at low temperature (less than 85°C or 185°F). This results in low stored energy in the coolants, so that a break in the primary coolant system does not result in the loss of primary inventory because of coolant flashing, and the confinement system will not be subjected to any significant pressure increase in the event of a large pipe break.

The engineered safety systems include highly reliable instrumentation systems designed to detect accident conditions and rapidly shut down the beam.

1. T/B Evaluation of Hazards and Accidents. Based on the Preliminary Evaluation of Hazards, it is concluded that the most significant hazards for APT are associated with the release of the inventory of radioactive material in the target/blanket. A preliminary list of target/blanket initiating events that could lead to radiological releases has been developed. This list is included in Table 1. Evaluation of these accidents will be a major portion of the PSAR.

2. Accident Mitigation. The large-break LOCA in the tungsten neutron source primary coolant system outside the cavity vessel is the most challenging design basis accident and is discussed here as it exemplifies the levels of accident mitigation strategy. The strategy for accident mitigation is to ensure a beam shutdown and decay heat removal. The beam shutdown is a redundant and diverse safety class system. For the LOCA, the primary coolant pumps are also stopped. The residual heat-removal system is the first line of defense to remove the decay heat and provide for the long-term cooling of the tungsten neutron source. The residual heat-removal system consists of two independent, forced-flow cooling systems for increased reliability (only one system is needed to remove the decay heat). The result is that the coolant in the tungsten neutron source remains subcooled during the initial drain-down period, and the fixed headers remain full of subcooled liquid to enable operation of the residual heat-removal system to remove the decay heat and provide long-term cooling of the tungsten neutron source. Preliminary simulation of the residual heat-removal system shows that the tungsten rods are completely cooled (70°C) at 600 s with an residual heat-removal system flow of 4% of the steady-state flow rate.

3. Cavity Flood System. The Cavity Flood system will be activated to flood the cavity vessel and remove the decay heat if the temperature measurements indicate that the residual heat-removal system is not maintaining the coolant in a subcooled condition. Even if the residual heat-removal system is totally ineffective, the inventory of coolant in the fixed headers and piping inside the cavity vessel are designed to keep the tungsten neutron source from overheating for approximately 30 h as the coolant heats up and boils off, which leads to uncovering the top of the tungsten neutron source. Thus, there is significant time to activate the cavity flood system before it is required to prevent the tungsten neutron source from overheating.

When the Cavity Flood system is activated, two sets of valves open to flood and vent the cavity. The target/blanket storage pool, located close to the cavity vessel, is used as a source of water for the cavity flood. The cavity flood system is designed with both redundancy and diversity to ensure initiation of cavity flood and prevent inadvertent initiation. The flood lines will go to the bottom of the cavity. The vent lines will come from the top of the cavity vessel and will go into the target/blanket storage pool through a sparger so that any steam will be condensed. In experiments on the vaporization of tungsten, the steam was condensed in this manner and it was found that the tungsten aerosols were effectively collected in the condensate suggesting this as an effective means to reduce potential APT releases for severe accident conditions.

When the cavity is flooded by the Cavity Flood system, there are several mechanisms to remove the heat from the in-vessel components. First, there is the sensible heat from the cavity flood coolant that is added. Then there is the mass of the internal structures that are at low temperatures (particularly the shielding). Next there is the heat removal resulting from the coolant boiling off. The steam formed will be vented and condensed in the target/blanket storage pool. If the vents have not been opened, relief valves that also discharge to the pool will provide a vent path.

All of these heat transfer mechanisms provide a very slow heatup of the components in the cavity. Eventually, coolant inventory will have to be made up or forced cooling provided. The forced cooling mode of the flooded cavity is considered the ultimate heat sink. The function is provided by forced circulation of the cavity water from the cavity to the target pool. The target-pool cooling system will then maintain the target-pool temperatures with an external cooling loop and air heat exchangers.

In addition to the passive and active cavity flood heat-removal systems, there are other heat-removal systems that if operating can be used to cool the cavity coolant in the tungsten heat-removal primary system during a LOCA. These include the blanket-cooling system, the shield-cooling system, and the window-cooling system.

4. Radiation Cooling of the Tungsten Target. If the residual heat-removal system and the cavity flood injection system were both to fail, the tungsten neutron source would eventually boil dry and heat up from the decay heat. This would be delayed for at least 20 h because of the large water inventory in the fixed headers inside the cavity.

Analyses have shown that radiation heat transfer from a dry target to the surrounding structures after 20 h will result in maximum target rod temperatures of 1000°C. At these temperatures, the Inconel clad on the tungsten rods will remain intact and there will be no interaction with the steam and tungsten to cause oxidation and vaporization of the tungsten rods. The result will be no radionuclide release from the tungsten neutron source for the loss-of-coolant events.

C. Tritium Separation Facility

The primary hazard in the tritium separation facility is exposure of workers to tritium oxide. The dose from elemental tritium is 10,000 to 30,000 times less than that from tritium oxide. As tritium separation facility contains only elemental tritium (0.1% tritium oxide assumed for conservatism), the hazard from a release of tritium separation facility inventory without oxidation is minimal. Therefore, the event of concern for tritium separation facility is a release with oxidation. To minimize the risk of exposure to the pubic, the material at risk was limited by Administrative Control. The limits are based on two events, a release of the entire tritium separation facility inventory in a full facility fire and a release from a single-point source within tritium separation facility with oxidation. To ensure conservatism in this evaluation, these evaluations assumed 100% oxidation of the available tritium over a 3-min time frame and used the limiting site location for the evaluation. These assumptions provide significant margin in the design to account for changes that may be required during preliminary and final design.

Worker protection within the tritium separation facility is based on tritium operational experience at existing DOE tritium facilities. Protection for workers is mainly provided by a combination of a secondary tritium confinement around tritium processing equipment with an inert atmosphere and tritium cleanup systems. Should an event cause a breach of both the process confinement and the secondary confinement, the processing room and heating ventilation and air conditioning system direct the release away from the workers and up a stack. Tritium monitoring in the tritium separation facility alert the operators to leave the processing area. Because the number of events that can cause a double breach of tritium separation facility confinements along with oxidation are limited, the risk for worker exposure within tritium separation facility is minimal.

D. Balance of Plant

The balance of plant provides support functions to all areas of APT. The hazards associated with the SSCs supported by the balance of plant are described in the accelerator, tritium separation facility, and target/blanket discussions above. As a result, the unique hazards associated with the balance of plant are mainly standard industrial hazards. Prevention and mitigation of these hazards are addressed by OSHA and other federal, state, and local rules/laws, in addition to national consensus codes and standards. In general, the balance of plant

SSCs are designed, constructed, maintained, and tested using commercially proven technology and national consensus codes and standards.

One set of hazards treated in the balance of plant section are the hazards associated with the target/blanket retargeting activities (e.g., direct radiation, dropping the target, and loss of cooling during transfer). To minimize the hazards, a single failure-proof cooling system will be provided for use during the transfer. However, the transfer will not take place until the target/blanket modules are self-cooling in air. The transfer is performed remotely in a shielded confinement area (including filtered exhaust) to prevent direct worker exposure. The crane operations will employ US Nuclear Regulatory Commission standards for critical lifts. With these design and administrative features, the hazards from an accident during retargeting activities will be minimized.

The water treatment system will have concentrations of radioactivity that could also represent a concern to the worker, namely, the primary target, blanket, and window water purification systems that will contain some radioactivity that will be collected in the resin beds. The extent of the hazard will be analyzed in the PSAR. The potential for release of this inventory is small, and an administrative control limiting the inventory is provided to ensure that the risk to the public is negligible.

The radwaste facility will contain liquid, solid, and gaseous waste in regulatory approved shipping containers. Packaging of low-level waste within the facility represents negligible risk to the worker and the public.

IV. CONCLUSIONS

The safety of APT is an integral part of the design and is assured through a program that places early emphasis on understanding the hazards and then developing a design that (1) emphasizes the elimination and minimization of the hazards, (2) is designed to prevent accidents that could cause existing hazards to be realized, and (3) includes defense-in-depth through the use of redundant and diverse features for accident mitigation.

The safety program will comply with DOE orders and many national consensus codes and standards. Many inherent and design features are utilized to enhance the safety of APT. These include

- the use of multiple, successive barriers against the release of radioactivity, which are designed and constructed so they will not be jeopardized by abnormal occurrences (e.g., equipment failure, human error, or natural phenomena such as earthquakes);
- the use of redundant and diverse engineered safety features such as beam shutdown, cavity flood, and residual heat-removal systems;
- the use of administrative controls to limit and control hazards, monitoring systems for detecting abnormal events;
- emergency plans and implementing procedures to minimize the effect of an abnormal occurrences; and
- the implementation of programs such as radiation protection, chemical safety, fire protection, training, maintenance, quality assurance and conduct of operations.

With these features, APT will ensure a safe and reliable tritium supply for our national needs.

TABLE 1
PRELIMINARY EVENTS LIST

Tritium Separation Facility fire with tritium release and oxidation
• Accelerator misdirection/misfocusing of the High-Energy Beam (assumed loss of confinement)
• Loss-of-accelerator tunnel confinement (tunnel purge of normally activated air)
• Large-Break LOCA in Tungsten or Blanket Heat-Removal Primary System outside or inside the cavity.
• Small-Break LOCA in Tungsten or Blanket Heat-Removal Primary System outside or inside the cavity.
• Loss of Offsite Power or Station Blackout
• Loss of Flow Accident Tungsten or Blanket Heat-Removal Primary System
• Loss of Secondary Heat Sinks
• Helium -3 System Break
• Explosion Causing Tritium/He-3 Release
• Resin Release resulting from overpressure, fire, or operation
• Loss of Cavity Vacuum System
• LOCAs, LOFAs, LOHSAs • Beam Stop Primary/Secondary Cooling Systems • Window Primary/Secondary Cooling System • Shield Primary /Secondary Cooling System •
• Spurious Operation of Cavity Flood Valves
• Target Module Handling Accidents
• Flow Blockage in Different Cooling Systems
• Beam Expander Magnet Failure Causing Beam Focusing Accident
External Hazards • Seismic • Flood • Wind and Tornado • Lightning • Fire •
Man-Made Hazards • Chemical Release in nearby facilities • Internal Flooding • Facility Fire • Radioactive Release in nearby facilities • Airplane Crash •
• Liquid releases of hazardous material