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EFFLUENT TREATMENT FOR NUCLEAR THERMAL PROPULSION GROUND TESTING

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Sandia National Laboratories

Ground testing of fuel, fuel elements, and engine assemblies at a suitable facility is required to support the development of nuclear thermal propulsion (NTP) systems. Given the current Environmental Safety and Health (ES&H) regulations, policies, and guidelines in the USA, it is not planned today to vent the potentially contaminated hydrogen that these tests will generate directly to the environment. In order to minimize the potential safety and environmental impacts of NTP ground tests, the gaseous reactor effluent needs to be confined, treated, and/or scrubbed of radioactive fission products prior to its unrestricted release.

Objectives

Define Treatment Functions
Review Concept Options
Discuss PIPET ETS Concept
Outline Future Activities

Over the years, several different options have been evaluated by Sandia National Laboratories to either process the hot hydrogen effluent simultaneously with the test being conducted or configure the test facility in a manner that real time processing is not required. The evaluation effort was initiated by identification and formulation of a wide range of concept options to treat NTP test article exhaust. The concept options considered ranged from closed cycle (venting the exhaust to a closed volume or recirculating the hydrogen in a closed loop) to open cycle (real time processing and venting of the effluent). A number of variations of these general concepts are still under consideration. This paper defines the functions any effluent treatment system must perform, reviews the various concept options to handle effluent from nuclear thermal propulsion system ground tests, presents the current lead effluent treatment concept for the PIPET project, and outlines future effluent treatment studies to be performed.

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Reactor Exhaust

Hydrogen Flow at 1 - 40 kg/s
Temperatures In Excess of 3000 K
Trace Concentrations of Particulate, Volatile Species, Halogens, and Noble Gases
Entrained Core Material and Debris

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Prismatic (NERVA Derived), particle (PBR and Pellet bed), and refractory (Cermet, Wire Core) fuel forms are all candidates for ground testing as a part of a NTP development program. Consideration of these varied concepts leads to a consistent set of functional requirements for any system designed to treat the reactor exhaust during ground testing. In all cases, fuel operating temperatures in the range of 2700 - 3400 K are planned. Significant quantities of cryogenic hydrogen will be required to cool NTP reactors tested under prototypic conditions. Small fuel element test reactors with powers on the order of 50 MW would require 1 kg/s coolant flows while large ground test of reactors with powers as high as 2000 MW would require coolant flows in the range of 40 kg/s.

As the hydrogen coolant flows through a fuel element and is heated by direct contact with the nuclear fuel, it can be expected to become contaminated with fission products and/or fuel particulate. The potential for the generation of other hazardous compounds within the hydrogen also exists. The risk of significant contamination is especially high early in the development process when new and advanced fuel forms are expected to be tested. The reactor exhaust can also be expected to contain significant quantities of core material and debris. The effluent treatment system design must allow for the potential of significant core failure and relocation that may occur during the development of any NTP concept.

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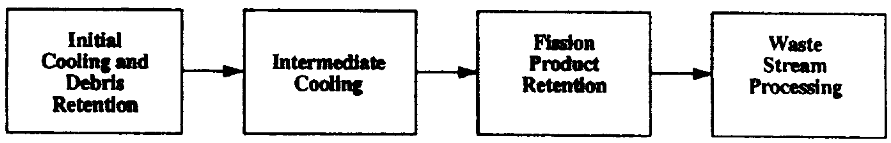
Effluent Treatment Functions



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Any system designed to treat the exhaust from a solid core NTP ground test reactor must perform four basic functions:

1. Initial cooling of the hot reactor exhaust to temperatures compatible with normal engineering materials. In addition, any debris and large particulate ejected from the core must be retained and maintained in a subcritical configuration.

2. Intermediate cooling to temperatures at or below atmospheric. While this cooling stage is not necessary, its inclusion in the system enhances the performance of many concepts.

3. Fission product retention to prevent uncontrolled release of contaminants to the environment. This stage must be designed to retain small particulate, halogens, noble gases, and other volatile species.

4. Waste stream processing to properly handle retained fission products, cleaned or processed hydrogen effluent, and any other potentially contaminated fluids introduced in or generated by the system.

The collection of components that performs these functions is normally referred to as an effluent treatment system (ETS).

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Effluent Treatment Categories

Closed Volume Systems
Delay and Accumulate Effluent

Open Systems
Real-Time Effluent Processing

Closed Loop Systems
Recirculate Effluent as Coolant

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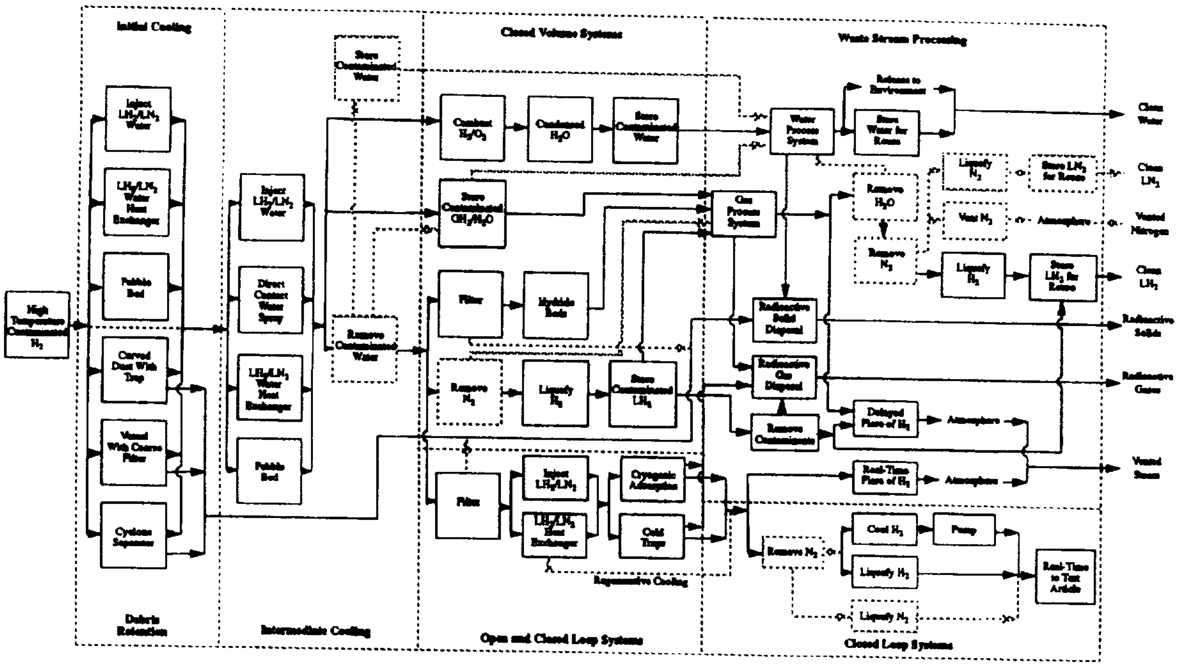
ETS concepts can be grouped into three broad categories: closed volume systems, open systems, and closed loop systems. Closed volume systems delay and accumulate the effluent generated during reactor power operations and then process the effluent at much reduced flow rates at some time after power operations. Closed volume systems include concept options such as venting the effluent to storage vessels or metal hydrides. In an open system, the effluent is processed and vented to the atmosphere as it is produced during reactor power operations. Open systems are characterized by large capacity filtration and adsorption equipment. A closed loop system performs real time processing of the effluent and then recirculates the hydrogen to the reactor inlet to be reused as coolant. Care must be used when comparing a closed loop system to other types of ETS concepts. The closed loop system both treats the reactor exhaust and performs the additional function of supplying coolant to the reactor inlet. The appropriate functional relationship is maintained when a closed loop system is compared to another ETS concept in combination with the concept and components used to supply coolant to the test reactor.



Effluent Treatment Options

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A map of effluent treatment options is shown. The high-temperature contaminated hydrogen effluent is shown entering on the left. Waste products resulting from the treatment process are should on the right. The major functional divisions of initial cooling, debris retention, closed volume systems, open and closed loop systems, and waste stream processing are labeled and outlined in dashed lines. Tracing a path through this figure (with appropriate consideration of branching) will define a complete functional effluent treatment system.

The commonalities of ETS component options and the impacts of component choices are illustrated. Each of the three categories (closed volume, open, closed loop) of effluent treatment concepts have the same options for components to perform the initial cooling, debris retention, and intermediate cooling functions. The concepts differ in the components used for fission product retention and waste stream processing. The choice of the method used for initial cooling can also influence the components that must included in the intermediate cooling, fission product retention, and waste processing stages. Optional downstream functions which may be required (dependent upon upstream component choice) are shown with dotted lines.

Concept Evaluation

- Total System Approach
- Reliability and Redundancy
- Passive Systems
- Avoid Exotic Materials and Concepts
- Maintenance, Inspection, and Testing
- Support and Posttest Processing Systems
- Expansion Potential
- Capital and Life Cycle Costs
- Decontamination and Decommissioning

Evaluation of effluent treatment concepts should be performed from a total system approach considering potential environmental impacts, safety, operations, potential future activities, and total cost. Any system designed must have a high degree of reliability and redundancy. Passive systems, such as blowdown rather than pumping, should be employed whenever practical. Exotic materials and concepts should be avoided. Steps should be taken to minimize occupational exposure during required in-service maintenance, inspection, and testing. Performance of the maintenance and inspection using remote or robotic means should be considered. The ETS support systems (coolant storage, water removal, etc.) and post test processing systems (decay heat, pebble bed heat, waste processing, etc.) can have significant impacts on overall system complexity and cost. The potential for future expansion should be considered. Any ETS concept is, to a first approximation, a power limited system. If it is desired to significantly increase reactor power (and thus flow) it would be necessary to significantly increase the size of the velocity limited components or to use process trains in parallel. A total energy limit, defined by the system storage capacity (coolants, heat sinks, closed volume fission product retention, etc.), also exists for an ETS. Both the first and the life cycle costs of system options should be evaluated. Evaluation to date has shown that the use of large complex equipment and systems should be minimized for a limited testing program since a large number of tests are required to offset the increased capital cost with decreased operating costs. The system end of life decontamination and decommissioning costs should also be considered.

PIPET ETS Envelope

Maximum Reactor Power		1 GW
Duration at Maximum Power		240 sec
Duration at 40 MW Power	≥	1 hr
Maximum Flow at 3000 K		20.4 kg/s
Maximum Flow at 1100 K		66.4 kg/s
Inlet Pressure at Maximum Power		1.4 MPa
Inlet Pressure at 120 MW		0.4 MPa

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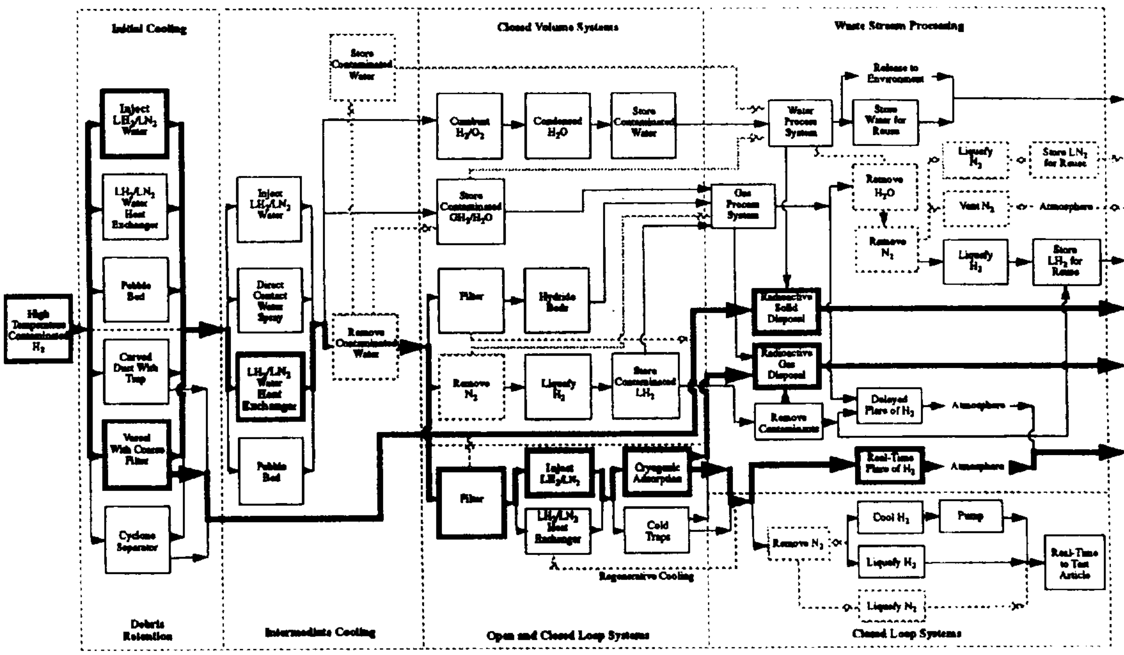
The current PIPET effluent treatment system is designed to support operation of ground test reactors at power levels up to 1 GW. The maximum duration of continuous full power operation is limited by the available coolant storage. The current design will support operation of 1 GW test reactors with a 3000 K exhaust temperature for a duration of 240 sec. Duration is increased if the reactor is operated at either a lower power level or a lower mixed mean inlet temperature. Durations well in excess of 1 hour may be obtained by the current ETS design for reactor powers in the range of 40 MW. The system volumetric flow rate is limited by the interstitial velocity in the system filtration and adsorption components. This leads to an inlet mass flow rate limitation that is a function of the effluent mixed mean temperature. The maximum inlet flow rate is 20.4 kg/s at a 3000 K inlet temperature. As the effluent temperature is reduced, the maximum allowable inlet mass flow rate increases. At a mixed mean effluent temperature of 1100 K, the allowable inlet mass flow rate is 66.4 kg/s. The volumetric flow constraint also establishes the system operating pressure limits. In order to reduce the size of the system components, the ETS was designed to operate at an inlet pressure of 1.4 MPa for the maximum flow and power conditions. This design pressure is sufficiently below the reactor design operating pressures (6.9 MPa chamber and 3.4 MPa throat) to insure decoupling the test article pressure response from that of the ETS. As the reactor power (and inlet flow) are reduced the system operating pressure may be reduced while a constant volumetric flow rate is maintained. At a reactor power of 120 MW the current ETS could be operated at an inlet pressure as low as 0.4 MPa.



PIPET Effluent Treatment Concept

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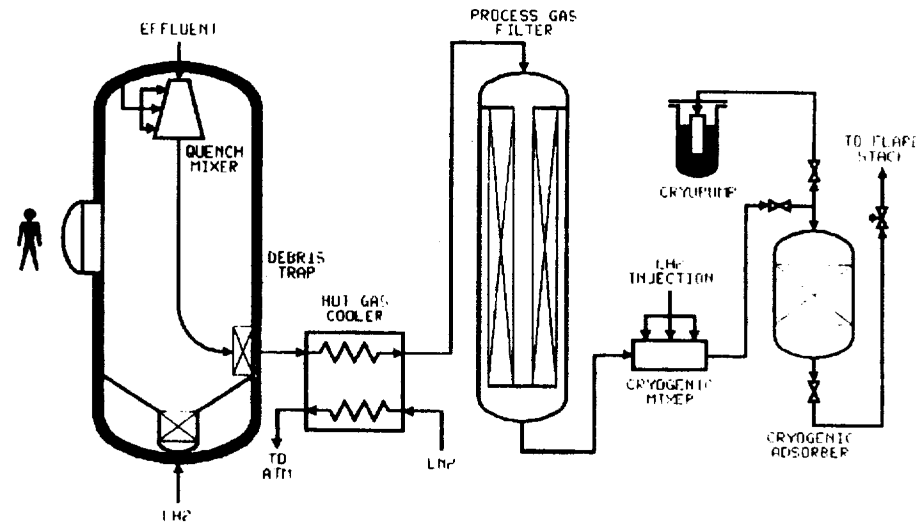
The effluent treatment concepts illustrated were evaluated during the development of the PIPET concept (shown in heavy lines). Concepts in addition to the lead concept (including water injection, gasholder, hydride, heat exchanger, pebble bed, and closed loop systems) have been developed to high levels and are still under consideration. The lead PIPET effluent treatment concept is an open system that uses liquid hydrogen injection for initial cooling, a liquid nitrogen heat exchanger for intermediate cooling, granular filters to remove particulate, liquid hydrogen injection to cool to cryogenic temperatures, and cryogenic charcoal adsorbers to remove halogens, noble gases, and other volatile species. A flare stack combusts the treated hydrogen effluent prior to venting to the environment.

Provisions are included to handle both the solid contaminants retained in the debris trap and gaseous contaminants retained in the cryogenic adsorbers. Access is provided to remove debris retained in the trap between operations. The filters and adsorbers are designed to retain the trapped particulate and halogens for the life of the facility. However, the noble gases are only retained in the adsorbers when cryogenic temperatures are maintained. When the adsorbers warm, the xenon and krypton will off-gas. Provisions for two procedures for the long-term disposal of the noble gases are incorporated into the design. The adsorbers may be isolated (valves included in the design) (1) to allow the noble gases to decay prior to releasing to the environment in a controlled manner or (2) to allow the noble gases to diffuse to a cryopump (included in the current design) to collect and concentrate the contaminants for appropriate disposal.

PIPET ETS CONCEPT



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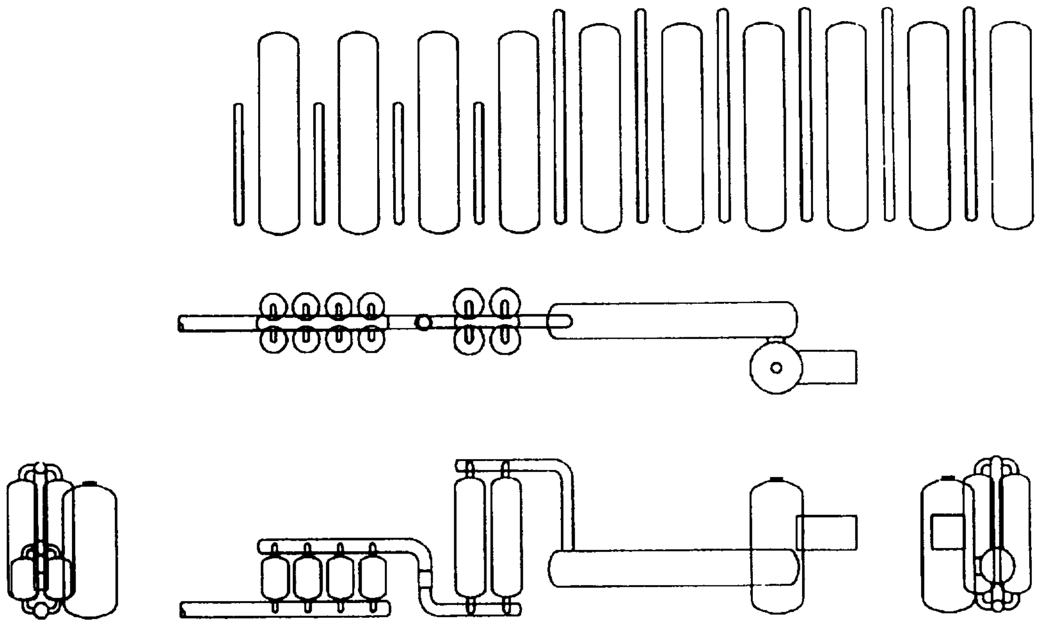
The lead PIPET ETS concept is shown. The initial quench mixer (located in the debris trap) cools the effluent to 1100 K (a reasonable material upper limit temperature for stainless steel). The debris trap is a large jacketed liquid hydrogen cooled pressure vessel (~9.1 m x 5.5 m ID). A coarse filter is located at the exit of the debris trap to serve two functions: (1) to retain large particulate (on the order of 300-500 micron) in the debris trap and (2) to provide a large surface area and thermal mass for the plate out of any high temperature aerosols prior to leaving the debris trap. Access to the debris trap interior for inspection and debris removal is provided through an airlock. A large (~21 m x 3.4 m ID) liquid nitrogen to hydrogen tube in shell heat exchanger cools the effluent to ambient temperature. The heat exchanger cold side is operated at a pressure above that of the effluent stream so that leaks will not bypass the process train. Large (~9.1 m x 2.7 m OD) radial flow granular filters remove small particulate. The effluent enters by the inner annulus, flows radially outward and is collected in the outer annulus. A second liquid hydrogen injection quench mixer is used to cool the effluent to the 160 K cryogenic adsorber operating temperature. Large (~3.0 m x 2.4 m OD) axial flow cryogenic activated impregnated charcoal adsorbers remove halogens, noble gases, and other volatiles. A pressure regulating valve is located downstream of the cryogenic adsorbers to control the system operating pressure. Active pressure control during startup and shutdown may allow system operating pressure to be maintained sufficiently below the reactor operating pressure for decoupling of the test article pressure response from that of the ETS.



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A potential layout of the lead PIPET effluent treatment system concept has been developed. Top, front, left side, and right side views are shown. The liquid hydrogen and liquid nitrogen storage vessels (with their associated gas pressurization storage) are shown in the top view. Piping sizes range from 0.5 to 1.5 m diameter. Four granular filters manifolded in parallel are required by the current design. The eight required cryogenic adsorbers (manifolded in parallel) are also shown.

Future Activities

SEI Requirement Impacts
- **Increased Reactor Power**
- **Extended Duration**
- **Altitude Simulation**

Single Failure Evaluation

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The impacts of SEI requirements on effluent treatment system design will be evaluated. These requirements include operation at increased reactor power, extended periods of continuous full power operation, and decreased system backpressure for altitude simulation. All of these design requirements may have significant impacts on ETS concept selection, design, and cost. Operating at increased reactor power (and flow) requires increased storage capacity for closed volume systems and either increased component size or parallel process train for open and closed loop systems. Increased duration requires large storage capacities for both open and closed volume systems. The need for low ETS operating pressures to support altitude simulation requires sufficient pressure recovery from the high-speed flow to overcome the system backpressure. Since many of the system components will be sized based upon flow velocity, the overall system size can be expected to increase as operating pressure decreases. The potential exists to incorporate a diffuser into the debris retention component design. Injectors or ejectors could be used to lower the system inlet pressure and cool the effluent stream.

Critical system functions (initial cooling, fission product retention, etc.) should be performed in a manner such that a single failure will not lead to loss of ETS function and fission product releases to the environment. The impacts to the public and the environment of ETS single component failures will be assessed. Appropriate features will be incorporated into the system design to mitigate any negative impacts.