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Safety Features of Subcritical Fluid Fueled Systems

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Abstract. Accelerator-driven transmutation technology has been under study at Los Alamos for several years for application to nuclear waste treatment, tritium production, energy generation, and recently, to the disposition of excess weapons plutonium. Studies and evaluations performed to date at Los Alamos have led to a current focus on a fluid-fuel, fission system operating in a neutron source-supported subcritical mode, using molten salt reactor technology and accelerator-driven proton-neutron spallation. In this paper, the safety features and characteristics of such systems are explored from the perspective of the fundamental nuclear safety objectives that any reactor-type system should address. This exploration is qualitative in nature and uses current vintage solid-fueled reactors as a baseline for comparison. Based on the safety perspectives presented, such systems should be capable of meeting the fundamental nuclear safety objectives. In addition, they should be able to provide the safety robustness desired for advanced reactors. However, the manner in which safety objectives and robustness are achieved is very different from that associated with conventional reactors. Also, there are a number of safety design and operational challenges that will have to be addressed for the safety potential of such systems to be credible.

INTRODUCTION

Accelerator-driven transmutation technology (ADTT) has been under study [1] at Los Alamos for several years for application to nuclear waste treatment, tritium production, and energy generation. Recently, application of this technology to the disposition of excess weapons plutonium [2] has been considered. The goals for this application are to achieve efficient plutonium burning without involving fertile material, which would produce additional plutonium; to provide the potential for essentially complete destruction of unwanted plutonium; to minimize processing of fuel and wastes; to have inherent safety robustness; and to offset plutonium disposition costs through generation of electric power. Studies and evaluations performed to date at Los Alamos have led to the current focus on a fluid-fuel, fission system operating in a source-supported subcritical mode.

The molten salt technology [3] developed at the Oak Ridge National Laboratory is the basis for the fluid-fuel approach. The fission region is configured and a plutonium concentration is selected such that a desired level of subcriticality is achieved at the operating conditions. High energy protons from a nearby accelerator impinge on a neutron spallation target within the fission region (referred to as the blanket) to produce a continuous, intense neutron source to sustain the fission process at the power level desired. The LAMPF accelerator technology [4] at Los Alamos is the basis for the high current accelerator required. Spallation targets [5] that have been developed and used at Los Alamos and elsewhere for years form the technology base for the intense neutron source. The integration of these major elements into to a feasible system to achieve the desired goals is the thrust of ongoing activities at Los Alamos.

As part of the system conceptualization process, safety characteristics of such systems have been theorized and investigated. In this paper, key safety characteristics of molten salt, accelerator-driven systems are discussed and compared to the safety characteristics for conventional reactors from which the nuclear community, the scientific community, and the public have established their baseline safety perspectives. Through this comparison, a safety perspective for molten salt, accelerator-driven systems, which is radically different, is presented. This perspective also addresses the potential of this concept to conform to the safety expectations for advanced fission systems as delineated by the US Nuclear Regulatory Commission in its policy statement on the regulation of advanced nuclear power plants.

FUNDAMENTAL NUCLEAR SAFETY OBJECTIVES

Accelerator-driven subcritical systems involve sustained fission processes that produce power levels comparable to conventional power reactors. Thus, they can be expected to have large fission product inventories, which constitute hazards of a scale similar to those for conventional fission reactors. As such, a reactor-like nuclear safety approach should be employed. Fundamental nuclear safety objectives [6] universally applied to the design of fission reactors are 1) control of fission power, 2) adequate cooling, and 3) containment of radioactive materials. Because there are characteristics of fluid fueled systems that make them resemble nuclear processing systems, two additional safety objectives have been added. These additional objectives are 4) prevention of inadvertent criticality and 5) control of personnel exposure. All of these objectives should be emphasized during the design process. They also would be the focus of safety reviews and licensing processes.

Meeting these objectives is key to controlling the fundamental health and safety hazard associated with such systems, namely radiation exposure to operations personnel and the public. Control of power levels and provision of cooling, such that over heating does not occur at any location where power is generated, must be assured under all conditions (power operation, shutdown, cold or hot standby, various power levels, stages in systems life) and circumstances (component failures, system failures, accidents, etc.). Likewise, inadvertent criticality and large integrated radiation exposures to personnel must be prevented under all conditions and circumstances.

For such a system to be licensed in the United States, it also would need to have characteristics consistent with those delineated by the Nuclear Regulatory Commission (NRC) in its policy statement on regulation of advanced nuclear power plants [7]. This policy emphasizes the desirability of the following attributes:

- highly reliable and less complex shutdown and decay heat removal systems, using inherent or passive means;
- longer time constants and sufficient instrumentation to allow for more diagnosis and management prior to reaching safety system challenges and/or exposure of vital equipment to adverse conditions;
- simplified safety systems which, where possible, reduce required operator action, equipment subjected to severe environmental conditions, and components needed for maintaining safe shutdown conditions; such simplified systems should facilitate operator comprehension, reliable system function, and more straightforward engineering analysis;
- designs that minimize the potential for severe accidents and their consequences by providing sufficient inherent safety, reliability, redundancy, and independence in safety systems;
- designs that provide reliable equipment in the balance of plant (or safety system independence from balance of plant) to reduce the number of challenges to safety systems;
- designs that provide easily maintained equipment and components;
- designs that reduce potential radiation exposure to plant personnel;
- designs that incorporate defense-in-depth philosophy by maintaining multiple barriers against release of radioactive materials, and by reducing the potential for and consequences of severe accidents; and
- design features that can be proven by citation of existent technology or that can be satisfactorily established by commitment to a suitable technology development program.

These characteristics provide the safety robustness (simplicity, sluggish response, passive system reliability, reduced system interdependencies, reduced severe accident concerns, assured defense-in-depth barriers, greater clarity in safety analyses and margins, etc.) that is desired for advanced systems, the initial versions of which will have little operational history.

SAFETY FEATURES AND PERSPECTIVES

In the this section, a qualitative perspective on the manner in which accelerator-driven subcritical systems and conventional reactors meet the five fundamental safety objectives is presented. The apparent safety robustness, or lack thereof, associated with accelerator-driven subcritical systems also is addressed.

Control of Fission Power

Control of the fission rate and therefore power generation has been recognized as an extremely important topic for fission reactors since the beginnings of reactor theory. The response of a neutronically critical system is highly nonlinear and rapid; the initial response being related to the prompt neutron generation time and the longer term response being related to the addition of delayed neutrons from particular decaying fission products. Indeed, it is these delayed neutrons that make practical reactor control feasible.

A key design objective has always been to ensure reactivity control (and therefore control of fission power) through an understanding the reactivity changes that can occur in a system and to provide an effective response to those changes using engineered control and safety systems and/or inherent reactivity feedbacks. Reactivity control systems must be capable of preventing power levels that exceed specific limits, which are set to ensure fuel stability (no significant melting, movement, or dimensional changes), cooling sufficiency, and first barrier (clad) integrity.

To obtain a general sense of the relative responses of critical and subcritical systems to postulated reactivity insertion events, simple point kinetics calculations were performed. The postulated reactivity insertion rate was 1 $/s, and its duration was assumed to be 0.5 s and 1 s. No reactivity feedbacks were assumed in either case to simplify the understanding of the results. The initial multiplication in the subcritical system was assumed to be 0.96, and the initial power for both systems was assumed to be 500 MW. The results are shown in Fig. 1. As expected for the critical system, the power rises rapidly and continues to rise after the reactivity insertion is terminated. Without negative reactivity insertions from inherent negative feedbacks and/or insertion of neutron absorbers, the transients are unterminated. The response of the subcritical system is markedly different in that the power changes very little. The power is proportional to the inverse of the degree of subcriticality of the system. The degree of subcriticality initially is 1-0.96 or 0.04. At the end of the 1 s reactivity insertion transient, one dollar (for the plutonium fueled molten salt system considered, some of the delayed neutron are released beyond the boundaries of the core, making a dollar of reactivity approximately equal to 0.002) of reactivity is inserted, making the final multiplication of the system equal to 0.962 and the degree of subcriticality equal to 0.038. The power change is approximately 5%, and a new steady state is established.

A subcritical system appears to be robust in accommodating postulated neutronic upset conditions because the system's response is predictable and relatively insensitive (small power changes for large reactivity changes) as long as the degree of subcriticality is substantial. If the system is assumed to be initially at a multiplication of 0.98 and the same reactivity insertion event is postulated (1 $/s for 1 s), the power would change by approximately 11%. If the system is assumed to be initially at a multiplication of 0.99 and the same reactivity insertion event is postulated, the power would change by approximately 25%. By selecting a substantial degree of subcritically for an operating point, the system would have large margins for reactivity changes without becoming critical and thereby transitioning to the nonlinear response regime or becoming prompt critical without hope of control.

Although these large margins and the decoupling of power changes from reactivity changes are attractive from the standpoint of the potential for power excursions, it is also true that desirable feedbacks such as those from system temperature changes only weakly affect the

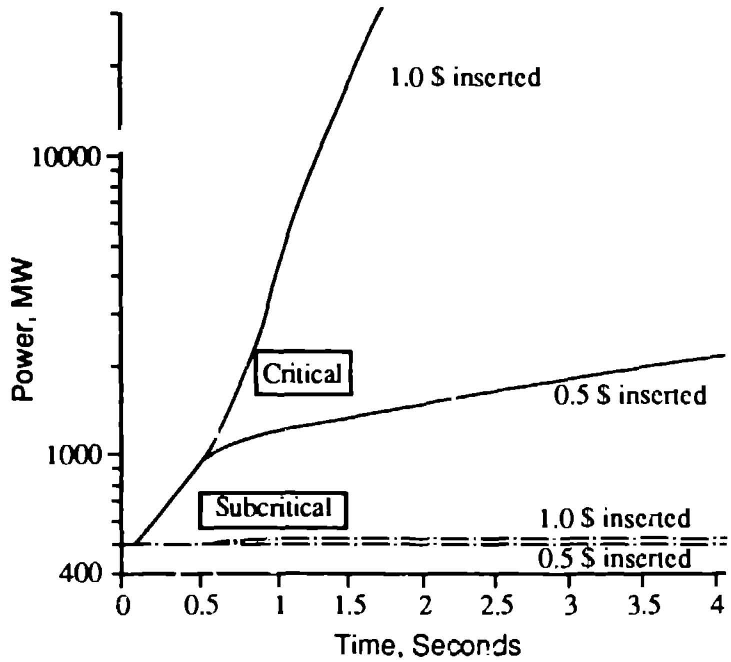

Fig. 1. Relative responses of critical and subcritical systems to reactivity insertions.

power. Thus, inherent power control is largely denied and must be replaced with active control. Active control with absorber rods also would not be particularly effective because of the power-reactivity decoupling. Thus, the active control would probably need to be done by varying the proton beam characteristics such that the neutron source intensity can be changed.

A second objective for reactor-type systems has always been to provide the capability for highly reliable and rapid termination of the fission process (scram) if the control system were to fail or unforeseen reactivity increases were to occur. Of particular importance is the prevention of the prompt-critical condition in which the power rises at such a high rate that the core and potentially other barriers against the release of radioactive materials could be compromised.

Normally reactors have mechanically inserted neutron absorber components (shutdown rods, safety rods, absorber balls, etc.) to provide the scram function. To achieve the desired high functional reliability of inserting these absorbers on demand, redundancy and diversity of components and systems are often employed. A high degree of assurance must be provided that core dimensional changes due to irradiation induced material swelling or thermal expansions do not prevent absorber insertion. Also a high degree of assurance must be provided that absorber insertion can be accomplished during seismic events. It is also important that the scram function be accomplished in the time interval required to intercept power excursions before safety limits are reached.

The situation is schematically portrayed in Fig. 2. For a typical reactor system, if the scram setting is reached, detectors sense the condition, the scram system sends signals to the actuation systems to insert the absorbers, the absorbers begin to move into the core as their inertia is overcome, negative reactivity is added to the core as the absorbers engage the core more and more, the power rise is arrested, and the system is shutdown after a short period of time. Because of the delays associated with absorber insertion, the power continued to rise above the scram point as shown. This power over-shoot for postulated transients must be predicted and included in the design of the shutdown system to ensure that safety limits are not exceeded. If a similar event were to occur in an accelerator-driven subcritical system, the delays would be limited to those associated with detection of the condition, scram system processing of the signals, and actuation of any number of beam interrupts. Once the proton beam is interrupted, the source neutron production stops nearly instantaneously and the power in the subcritical system drops promptly. Thus, the shutdown can be accomplished quickly, predictably, and reliably following detection of the need for shutdown. The need for in-core neutron absorber insertion with the associated mechanical complexities is eliminated. The complexities associated with "managing" the power over-shoot also are eliminated.

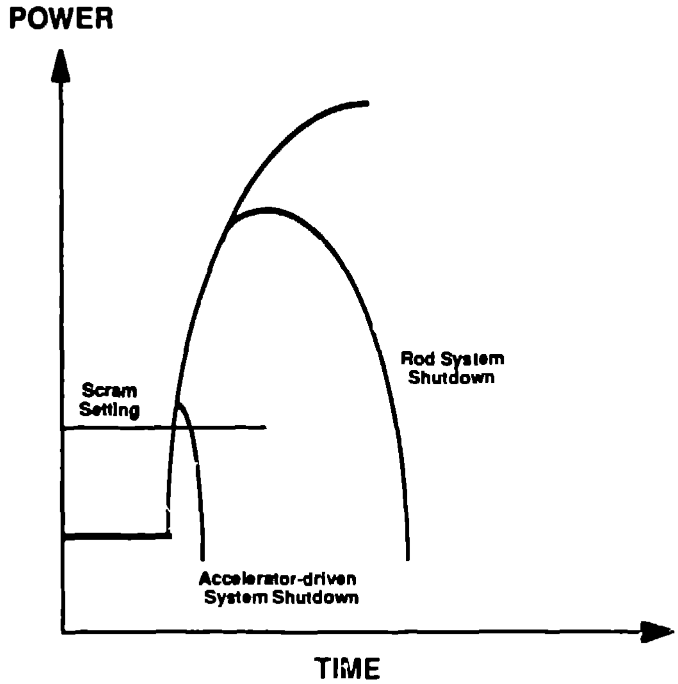

Fig. 2. Rapid shutdown potential for accelerator-driven fission systems.

Adequate Cooling

Assuring adequate cooling in all situations also has been recognized as an extremely important topic for fission reactors since the beginnings of reactor engineering. Because the integrity of the first barrier (for discussion purposes, the clad on fuel pins is considered the first barrier) is a key element in the defense-in-depth strategy for preventing the release of fission products and because this integrity is strongly linked to clad temperature, adequate cooling must be assured for normal power operations, for a variety of off-normal situations including accidents, and for shutdown with the associated decay heat from the fission products.

For conventional solid fueled reactors with high power densities and water coolants, the clad temperature can rise rapidly if cooling is interrupted locally. The rate of temperature rise is related primarily to the heat capacity of the core materials and the local power density. Because the clad temperature rise can be rapid, cooling interruptions due to degraded local heat transfer processes (such as departure from nucleate boiling) or insufficient coolant flow can not be tolerated. For the molten salt system, the first barrier is the primary system boundary (vessel, piping, heat exchanger tubes, etc.). The thermal response of this first barrier is linked to the heat capacity of the entire primary system, which is substantially larger than that of the core alone. As shown schematically in Fig. 3, the rate of temperature rise would be much lower if cooling is interrupted. This slow, system-wide response provides substantially increased opportunities to sense inadequate cooling conditions and to respond appropriately (such as scram, switching to emergency power, realigning valves, etc.). Thus, the molten salt system exhibits a thermal robustness that is attractive.

The molten salt system also exhibits robustness from the standpoint of heat transfer and heat transport in the core region. Again the point of reference is a solid fueled, rod-type core. The heat transfer situation is shown schematically in Fig. 4. The heat is generated in the solid fuel material and is transferred out of the fuel, across the fuel-clad gap, through the clad, and to

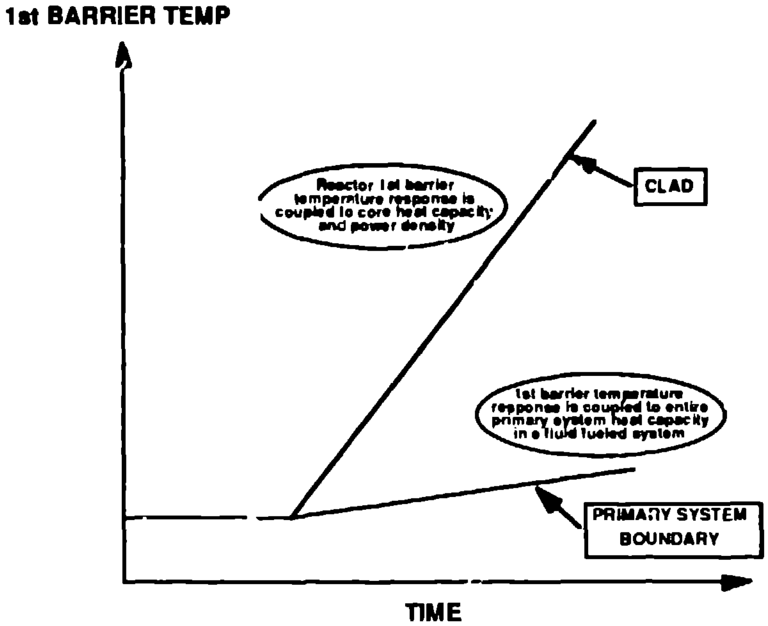

Fig. 3. Relative thermal response characteristics for solid and fluid fueled systems.

the surrounding coolant. The heat transfer processes include conduction, radiation, and convection. The overall heat transfer-heat transport process is sensitive to dimensional changes, fuel restructuring, fission gas content in the gap, coolant pressure, coolant subcooling, and coolant velocity. Many of these aspects can change substantially during core life, for different operating modes, and for off-normal and accident conditions. Thus, the overall heat transfer-heat transport process is complex yet must be known reasonably well to assure adequate cooling and protection of the first barrier under all circumstances. Also shown in Fig. 4 is a schematic of a typical molten salt core (in the accelerator-driven system it is referred to as the blanket) in which the salt flows through a graphite moderating structure. Because the fissioning materials are in the flowing molten salt, the heat is generated directly in the molten salt, which is also the heat transport medium. Thus, all coupled heat transfer-heat transport processes are eliminated in the core. This arrangement also appears to have a self limiting characteristic in that if cooling in the core (heat transport in this case) is inadequate, the coolant/fuel salt over heats, eventually boils, is ejected from the core, and effectively stops the fission process locally (fissioning materials removed).

The final aspect of assured cooling considered in this paper is that of decay heat removal, which also is extremely important for the protection of defense-in-depth barriers. A schematic comparison of the decay heat removal situation for the solid and fluid fueled systems is shown in Fig. 5. For both system, the challenge is to get the decay heat to an ultimate heat sink. The challenge of assuring an ultimate heat sink is the same for both systems. Again, however, there is the complexity in the solid fuel system of getting the heat from the compact core to the primary heat transport system. In the molten salt system, the decay heat is generated throughout the salt inventory in the primary system. Thus, this system has the possibility for predictable natural convection cooling to the primary system boundary and the possibility of radiant heat rejection from the primary system boundary to an external heat sink, if the individual systems are not too large. This could constitute a completely passive decay heat removal system.

Containment of Radioactive Materials

Because the accelerator-driven molten salt system operates at high power and involves a fission process, it has essentially all the hazards that are normally associated with conventional

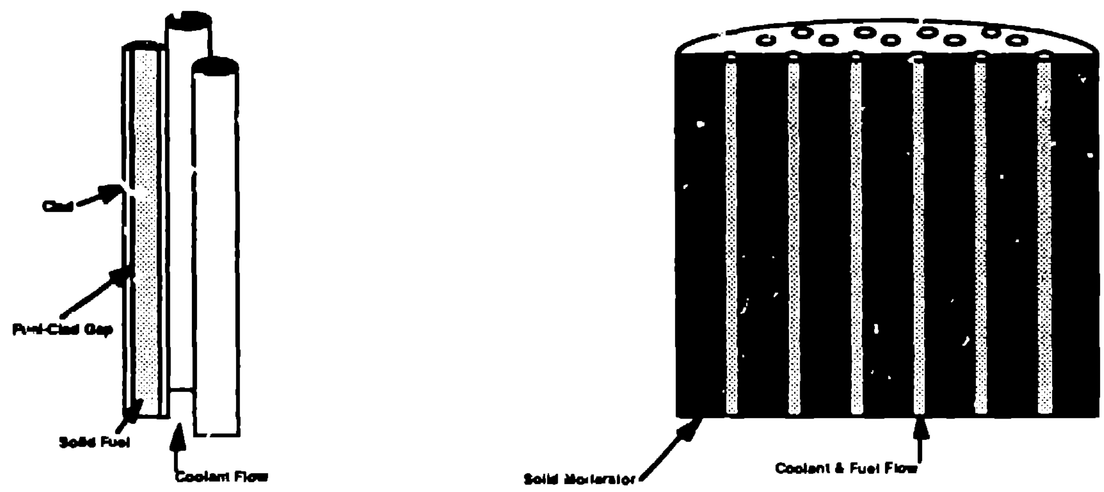

Fig. 4. Cooling arrangements for representative solid and fluid fueled systems.

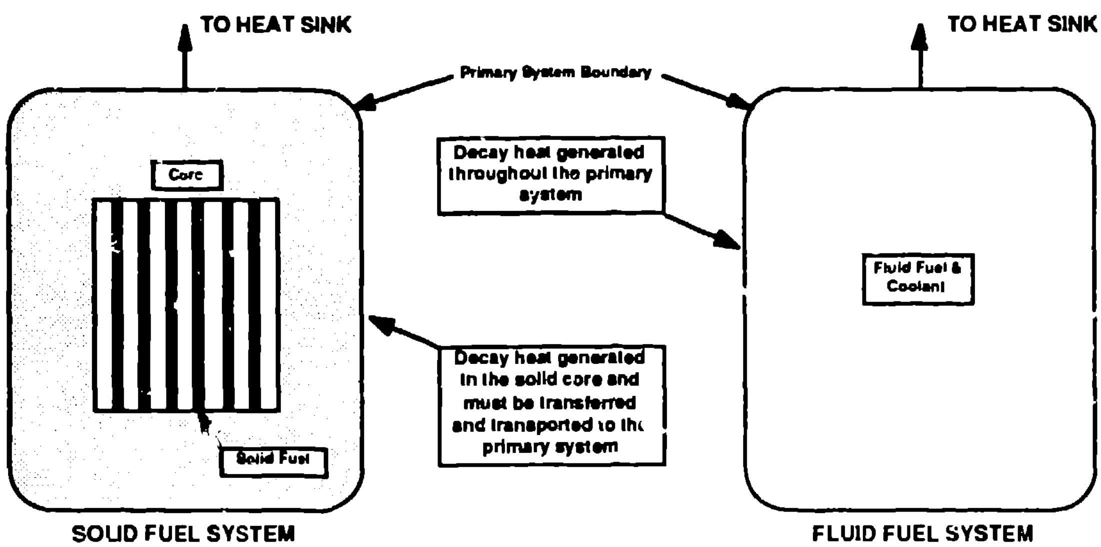

Fig. 5. Decay heat removal in solid and fluid fueled systems.

fission reactors, particularly with regard to fission products. The type and quantities of fission products are different for the molten salt system (gaseous fission products will not remain in the molten salt and will have to be collected and stored in special systems that are separate from the primary system), but will, never the less, constitute a formidable hazard. Thus, containment of the radioactive materials at all time and for all conditions must be accomplished for the molten salt system.

The challenge of providing appropriate defense-in-depth barriers will need to be met with a different approach for the molten salt system. In conventional reactors, the first barrier is a challenge to protect and to assure its function, but it has a limited life requirement (approximately 3 years and then it is replaced) and it is compartmentalized in the form of many individual sealed units (each fuel pin). Thus, if a few of the individual units of the first barrier fail for some reason, only a relatively small fraction of the fission product inventory is released to the next barrier. In contrast, if the first barrier (the primary system boundary) of the molten salt system fails for some reason, essentially all the fission product inventory in the salt will be released to the next barrier.

The options to deal with this challenge appear to be to assure high reliability in the performance of the primary system boundary, to provide a highly reliable and effective second barrier, or both. Because the first barrier is not in the core and therefore does not affect neutronic performance and is generally accessible, design flexibility should exist to make the primary system boundary highly robust and to provide inspectability by remote means. Although, engineering design layouts of various options for the second barrier have not been completed, the approach used for the Molten Salt Reactor Experiment [8] appears to have merit and to be feasible. Sealed vaults with appropriate heat removal systems, atmosphere control systems, spill recovery systems, etc. could be used. Finally, the defense-in-depth barrier strategy would be completed with a surrounding containment or confinement structure as appropriate. The barrier arrangements for a conventional reactor and for the molten salt system are shown schematically in Fig. 6.

Another special challenge for the accelerator-driven molten salt system is the integration of the beam transport equipment with the containment barriers. The proton beam can not pass directly through heavy-walled structures without substantial beam loss and the generation of significant heat and radiation. Some type of thin-window approach is necessary. To accommodate the conflicting requirements of barrier robustness and beam window thinness, it may be necessary to make the beam transport tube part of the barrier system. This would probably require the beam tube to be a reentrant thimble through the outer containment barrier, the vault barrier, and the primary system barrier. The target system and its associated thin window would be positioned entirely within this thimble.

Prevention of Inadvertent Criticality

Prevention of inadvertent criticality in conventional reactors is a relatively straightforward matter because it is a concern only for fuel handling, new fuel storage, and spent fuel storage. Because the fuel is in the solid state, is segregated into numerous individual assemblies, can be handled in a very controlled manner, can be monitored for structural deterioration, and can be stored in well characterized and robust structures (physical spacing and integrated neutron absorbers), it is extremely unlikely that an inadvertent criticality would occur.

In contrast, the molten salt system presents challenges in assuring that the location of all fissile material is known at all times. The potential for precipitation of fissile materials from the molten salt under various expected and postulated conditions must be considered. The

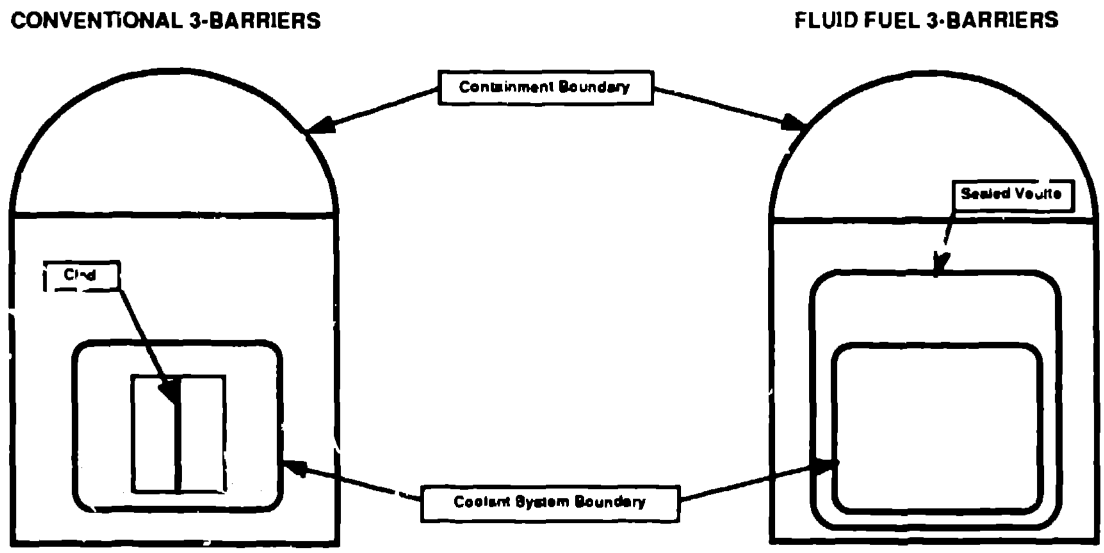

Fig. 6. Barrier arrangements for representative solid and fluid fueled systems.

potential for criticality in the fissile material feed system must be considered. The potential for criticality in the salt cleanup and processing system must be carefully considered. Salt storage systems may need to be designed to accommodate some precipitation should the molten salt temperature drop to the freezing point. Care will also be required to assure that spills and leaks accumulate in subcritical configurations. The opportunities for inadvertent criticality are certainly greater in the fluid fueled molten salt system compared to conventional solid fueled systems. The criticality concerns should be mitigated somewhat by the subcritical character of the molten salt in an accelerator-driven system. However, the concerns will also be dependent on the degree of moderation provided in the core/blanket design and whether the opportunity exists to substantially increase neutronic multiplication in ex-core regions where substantial salt might accumulate. With the exception of the feed system, inadvertent criticality would occur only in unoccupied, robust, vault-type structures and therefore would not present a direct hazard to workers or the public.

Radiation Exposures to Personnel

Integrated exposure to the operating staff of a conventional reactor power station has become a figure-of-merit for the quality of the operation; reliability of equipment; and the provisions in the design for ease of maintenance, inspections, testing, and repairs. The accelerator-driven molten salt system has the potential to present a considerable challenge to designer and operators relative to this figure-of-merit. The challenge has its origin in four characteristics of the accelerator-driven molten salt system. First, the fissions products distributed throughout the primary system produce extremely high radiation fields in all areas adjacent to the primary system and potentially high exposures during incident recovery operations (spills) or eventual decontamination and decommissioning. Second, delayed neutron production throughout the primary system activates all primary system equipment resulting in radiation exposure potentials even after decontamination. Third, the target and thimble systems will have limited life and require frequent replacement, leading to exposure potentials. Fourth, the use of a lithium based salt will result in the generation of substantial tritium, which will diffuse through the metallic boundaries and produce exposure potentials. All of these exposure potentials will have to be recognized in the design process, including those associated with postulated off-normal events, and special provisions will have to be included to protect workers during inspections, testing, maintenance, and repairs. A high premium will need to be placed on highly reliable equipment.

SUMMARY

The accelerator-driven molten salt system has the potential to provide robust, predictable, straightforward, attractive safety characteristics in the areas of power excursion prevention, assured shutdown, assured cooling, and energetic severe accident prevention. Containment of radioactive materials through a defense-in-depth strategy is feasible for this system, but presents the challenge of integrating the proton beam tube with the desired robust barrier systems. Inadvertent criticality will require special attention in the design because of the decreased predictability of the location of all fissile materials in a fluid fueled system. Also special attention will be required in the design to manage the increased potentials for exposures to plant personnel arising from the distributed fission products in the primary system, extensive delayed neutron activation of equipment, target system replacement, and tritium control. It should be noted that the positive safety effects that result from subcritical operation can only be realized if the subcriticality status of the system is continuously known and within required limits. This is a challenge, but some plausible approaches have been defined.

The fundamental safety objectives for reactor-like systems can be accomplished in an accelerator-driven molten salt system, albeit by very different means. Many of the desirable characteristics of advanced reactor systems delineated by the USNRC can be provided by such a system. Others of these characteristics, such as providing easily maintained equipment and components and reducing the potential radiation exposure to plant personnel will be design challenges.

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