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BEAM SHUT DOWN CONSIDERATIONS FOR LARGE ACCELERATOR-DRIVEN TARGET SYSTEMS

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ABSTRACT

While the potential hazards posed by large particle-accelerator driven spallation targets are greatly reduced in comparison to nuclear reactors capable of similar neutron production levels, they are significant, and require a safety-by-design approach to ensure there is little likelihood of accidental releases of target materials. Most postulated accident scenarios evolve very slowly, given the modest after-heat levels in spallation targets, and modest backup heat removal systems can prevent target damage. Similarly, events where problems develop with the accelerated particle beams are easily detected and can be quickly terminated. This leaves an interesting class of postulated accidents, where problems are postulated to develop in the target cooling system but there is a failure to recognize the problem and shut down the accelerator. Safety systems designed to detect such problems are likely to be reliable, but given the potential for serious target damage, there is incentive to further reduce the likelihood of this class of events. Options to do so are discussed.

I. INTRODUCTION

Particle accelerator and nuclear reactor technologies have developed for several decades along parallel paths, with an important similarity being the capacity to produce large numbers of neutrons, via fission (reactors) or spallation, which occurs when high energy particles slam into target materials. Because of improvements in particle-accelerator technology and economic, regulatory, and political difficulties in building new nuclear reactors, several large-scale applications of accelerator-driven spallation targets have been proposed in recent years. The accelerated particles can be ions, protons, or electrons/positrons (or possibly short lived particles, such as muons), but most proposed accelerator-driven spallation targets are based on proton accelerators.

A key part of any accelerator design involves "focusing" the beam in space and time. The proton bunches are grouped and concentrated using transverse magnetic fields and longitudinal electrical fields, in a continuing process throughout the acceleration of the beam, in order to overcome space-charge effects that tend to drive the particles apart and also to overcome the expansion due to thermal disorder in the beam ("emittance"). Thus, it is with considerable effort that the beam exiting the accelerator is largely constrained within a few millimeter diameter and within a time window of perhaps 30 picoseconds. The spatial distribution of the protons within the accelerator can be approximated as a two-dimensional Guassian distribution. If allowed to expand without focusing, the beam distribution many meters downstream would be strongly peaked in the center, making target thermal engineering difficult. Instead, designers generally include a two-dimensional beam expander, capable of creating a uniform distribution in the x and y dimensions, albeit with some significant peaking around the edges. Such a two-dimensional beam-expander was built and tested, with the data successfully compared against analytical predictions (see Figure 1).[1]

Even when fully expanded, a high-power particle beam deposits a large amount of energy, particularly in the front portion of the spallation target. Therefore, for large applications targets, coolant systems are designed to remove the heat and maintain target temperatures at safe levels. However, if there develops a significant degradation in the coolant system it could become imperative to either quickly restore target cooling or shut down the accelerator. It is not difficult to design if there exists a scenario that is likely to occur regularly, such as a pump trip, it is only rational to consider adding a little insurance such that the beam will be shut down reliably. Depending on the nature of the initiating events of concern, there may be several

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options for reducing any vulnerability to beam shut down failure scenarios.

II. SPALLATION PHYSICS AND APPLICATIONS

"Spallation" refers to nuclear reactions that develop when high energy particles (above 100 MeV per nucleon), such as protons, neutrons, pions, muons, or deuterons, interact with an atomic nucleus. Above energies corresponding to the DeBroglie wavelength of the incident particle, the particle interacts with individual nucleons within the nucleus. The initial collision between the incident particle and the target nucleus leads to an "intranuclear cascade", wherein individual nucleons or small groups of nucleons are ejected from the target nucleus. Should the incident particle energy exceed a few GeV per nucleon, the target nucleus could be "fragmented". Subsequent to the cascade process, excited nuclei "evaporate" off nucleons to reach the ground state. Most of these nucleons are neutrons, and many of the "spallation neutrons" result from the evaporation process, and thus are emitted isotropically, which is important in the target design.[2]

The spallation process is illustrated in Figure 2, which shows both the cascade process and the evaporative phase.[2] Also shown is the high-energy fission that can occur with heavy target materials such as lead and tungsten. Should actinides, such as uranium or thorium, be used as target materials, additional neutrons could be triggered by the fission.

The estimated numbers of usable (below 20 MeV) spallation neutrons per proton produced in five candidate materials as a function of incident proton energy are shown in Figure 3.2. In general, the greatest production is in the actinides, even without taking into account the multiplication from fission. An approximate fit to the lines in Figure 3 gives the following approximation for total N/P:

$$N/P = (E\ (\mathrm{MeV}) - 200) * \chi\,, \qquad (1)$$

where the χ's for lead, tantalum, tungsten, thorium, and depleted uranium, are approximately .033, .037, .039, .047, and .074, respectively. Note that one could evaluate an effective χ for a heterogeneous target, using computer simulations or experiments, although the energy dependence may not be linear.

Most proposed targets do not include actinides so as to avoid high level waste issues and other institutional and safety concerns. Instead, tungsten or lead is often chosen. Lead has the smaller neutron absorption cross section (0.17 barns, thermal), with tungsten being a much stronger neutron absorber (18.2 barns, thermal). However, lead has a low melting temperature, so target designers sometimes choose to utilize tungsten, reducing parasitic capture of neutrons through the use of high leakage geometry and possibly "decoupler" regions, which are designed to pass high energy particles exiting the target but to capture lower energy neutrons about to reenter the spallation target region.

For accelerator targets that contain no actinides, the radionuclide inventory is dominated by spallation products and activation products very near the target material in atomic number. This is readily apparent in Figure 4.[2] Obviously the dominant species will depend on whether the original material is tungsten, lead, or possibly mercury or tantalum. The trend indicated by analyses and data, is that comparatively few isotopes are of concern for either tungsten or lead.

III. SAFETY APPROACH

While there exists an after-heat issue for spallation targets, the heat generation rate after beam shut down is much lower than that after reactor trip, assuming actinides are not used in the spallation target. If severe damage occurs in the target cooling system, and the adverse circumstances continue many hours, one could eventually cause serious damage to a spallation target. Even so, the long delay before target damage, the lower level of hazards (compared to a reactor) in the target, and the likelihood that target materials would be unlikely to reach the environment (low energy system), make these events less disconcerting than the corresponding events postulated for nuclear reactors.

Accelerator beam trips based on problems within the accelerator are quite reliable, since the need to provide for a quick shutdown should the beam stray is an old problem. Designers long ago developed reliable means of monitoring the beam distribution along the accelerator. Shutting down an accelerator beam is almost trivial, since a simple cut in current will bring the machine down in less than 100 microseconds. Further, there are options to passively shut off the beam should the beam stray or intensify-using the equivalent of fuses.

In contrast, the technology of large-scale spallation targets is relatively new. The challenge is to monitor conditions in the spallation targets, such as temperatures, pressures, and coolant flow rates. This can be done using the same technology used to monitor conditions in a reactor. In practice, the likelihood of reliably shutting

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down the accelerator will be nearly equal to the likelihood of reliably determining there is a need to shut down the accelerator.

This leads to an interesting parallel to reactor safety, i.e., the possibility that an anticipated operating event might evolve without a significant decrease in heat generation. Clearly such events are less likely than those where the safety systems act to stop the fission or spallation process. However, the impact of the event could be much greater, providing incentives to drive the likelihood or the possible impact to an acceptably low level.

This all leads to the crucial question: just which events could be defined as Anticipated Operating Occurrences for accelerator-driven target systems, and how does one avoid significant consequences if the beam remains on for some plausible period of time. If this comparatively short list of events can be accommodated without damage, then the main accelerator-driven system safety challenges will revert to long heat-up events with low after-heat.

There are three apparent ways to deal with anticipated events that may require a beam shut down in order to avoid serious consequences. The first, and most obvious, is to make the event less likely. Second, one could make the system robust enough to ride out a mild perturbation in operations until the problem can be addressed. Third, one can increase the probability of shutting down the beam through the use of a simple and/or passive beam shutdown, thereby supplementing the active beam shut down system for specific scenarios. For example, if it is a trip of the primary coolant pumps that is the concern, then there are several ways to determine that the pump has tripped. Obviously, it is simpler to monitor a pump impeller speed than to infer a problem based on numerous temperature and pressure readings dispersed throughout a coolant system.

This is then a two-tiered defense against failure to shut down the beam when there is a target-cooling problem. The first line of defense is a highly redundant trip system that monitors all pertinent target system parameters. This system should recognize a significant problem anywhere one could develop. The second line of defense focuses on the most likely problems - particulary those that would likely occur during the life of the facility. The designer must make the initiating event less likely to occur, less likely to have an unacceptable consequence, or less likely to pass unnoticed - perhaps by establishing a simple and/or passive beam shut down. In combination, the two-tier approach should relegate such failure to shut down the beam events down into insignificance.

IV. OPTIONS 1 AND 2: REDUCE THE INITIATING EVENT LIKELIHOOD OR IMPACT

If the full, active target protection system is highly reliable, then it is initiating events in the once-in-the-facility-lifetime and higher range that need to be addressed. For a well designed system, this should leave only a few initiating events that require a beam shut down to avoid serious damage to the target. Having identified a crucial component, for example, if it is a loss of power to a pump that is the initiator of concern, the designer could provide redundant power supplies, thereby reducing the likelihood of the initiator.

In designing a coolant system, it may also be possible to normally operate with a redundant pump, such that the loss of a single pump leaves sufficient pumping capacity to cool the target even with the beam on. For example, if three pumps always run in parallel, when one drops out the coolant flow would likely drop by 20 to 25%. If the target and coolant system are designed with sufficient margin, it should be possible to operate indefinitely on 75 to 80% of full flow, albeit at somewhat elevated temperatures. This is an interesting option as one could eventually run 10 (or even more) pumps in parallel in order to ensure the flow could never decrease significantly in response to the loss of one pump. (In practice, this may be unattractive, since the operation of so many pumps implies more frequent pump failures, which could be self-defeating - it may be wiser to boost the thermal margin of the target instead.)

In practice it may be impossible to prevent a component from failing at least once in a plant's lifetime, even with extensive redundancy. In addition, the economic penalty associated with opening up larger coolant channels in a target may be unacceptable. If options 1 and 2 are eliminated, and the reliability of the broadly-based (many parameters monitored) beam shut down is insufficient to banish the postulated event from serious consideration, there remains the option of monitoring for a specific occurrence and designing a nearly fool-proof means of shutting down the accelerator.

V. OPTION 3: BEAM SHUT DOWN IN RESPONSE TO ANTICIPATED UPSETS

We can postulate a typical spallation target coolant system as consisting of a loop of circulating coolant, driven by one of more pumps through a heat exchanger, where the heat is transferred to a secondary coolant system. The heating in the target is fixed by the accelerator beam power, and the heat removal capacity of the secondary system may be limited by pumping capacity and ultimate heat sink temperature. This implies that a reduction in pumping capacity will cause the target temperatures to increase. The significance of that increase depends on the amount of pumping capacity lost and the thermal design margins in the target. For the sake of the remainder of the discussion, it will be assumed that: 1) it is not possible to design a pump with so much redundancy that it never fails (true), and 2) it is impractical to run enough parallel pumps as to make the loss of one acceptable- even with the beam full on (depends on design options and margins).

At this point, the designer must find sure means for monitoring the "Achilles Heel" of the system - the pumps in this case. The ideal system would be truly passive - such that if an important pump is not operating, the accelerator cannot possibly operate. An easy example of this would be if failure of the power circuit that supports the pump were the concern, the designer could use power from the same circuit to support both the pump and the ion source at the front end of the accelerator. If the circuit fails, both the pump and the accelerator lose power simultaneously (but the pump has more inertia, assuring a safe cool-down of the target). Unfortunately, loss of power circuit may not drive the loss of pumping probability. Instead, one needs to ensure the pump impeller is turning, and preferably, that coolant is flowing through the pump at the normal rate.

Tracking the impeller speed may be sufficient to address all pump-related initiators expected at least once in the facility lifetime. This would cover loss of power to the pump, mechanical and electrical failures within the pump, and even the "locked rotor" cases where something suddenly blocks or seizes the pump. In this case, the designer would monitor the impeller speed, possibly using the rotational motion to establish magnetic fields and/or currents. A passive system might use the magnetic fields or induced currents to either allow continued performance of the ion source or to interrupt performance of the ion source.

Depending on the system design, one might postulate cases where the target cooling can degrade unacceptably even if all the pump impellers are rotating normally. This would probably involve flow blockage, although most well engineered systems would not be vulnerable to serious flow blockages very often. Regardless, the designer could try to assure a beam shut down in response to flow blockages in the coolant pumps. For example, a fuse-like design might involve an electrically insulated wire running through the coolant stream downstream of the pump, and then running sufficient current through it that the coolant flow is necessary to prevent it from melting (or shorting out, should the insulator fail). If this could be achieved, the designer could again run some of that current through the ion source, passively shutting off the beam at the source if the coolant flow degraded significantly.

While totally passive safety systems are very attractive in principle, they are more difficult to implement in practice. There are always details to be resolved - such as how the passive system can be bypassed when starting up the machine or when one must run the machine in some off-normal mode. Usually, one must show experimentally that they will fail reliably - always when needed and only when needed. This does not mean passive safety systems should be avoided, only that there is considerable effort involved in converting an attractive concept into a viable system.

In the meantime, it is possible to design relatively simple electrical or computer based systems that will detect a loss of cooling capacity and shut off the beam. The essential design objective is to keep it simple and absolutely reliable - and, if possible, maintenance free. In principle, it is easier to design and test such simple active systems than it is for passive systems.

VI. SIMPLIFIED SYSTEMS FOR DETECTING TARGET COOLING PROBLEMS

Three characteristics are necessary in order to provide the desired reliability and simplicity. First, the sensing device, as well as the transmitter, must remain functional in the environment in which it is expected to operate. Second, the sensing device and its associated circuit shall de-energize to actuate its intended function. Third, power shall be supplied to the sensing and actuating circuit during all postulated abnormal events, and, upon loss of power, the actuating device shall perform it's intended function.

Loss of power to the coolant pumps and associated systems can be easily detected by a voltage relay on the power distribution circuit. This voltage relay would be energized at all times when the distribution bus voltage is normal. Although temperature and coolant flow monitors provide adequate assurance that the coolant system continues to operate normally, additional reassurance to detect a loss of coolant can be achieved by installing transformers and relays (CT's) on the coolant pump motor bus downstream of the motor starter. If the coolant pump motor current relays (CT's) fail to detect normal current conditions, the CT relay would initiate a loss of signal thus providing a beam shut down signal to the accelerator control system. This feature would detect such pump failures as locked rotor, no load conditions, and de-energized pump rotor.

Coolant flow is essential to maintain target temperatures within thermal tolerances. Coolant flow monitored using flow transducers immediately downstream of the pump(s) would provide assurance that the coolant pump(s) are supplying adequate coolant to the target. Coolant pump abnormalities such as loss of power, locked rotor, and other failures that will interrupt or significantly degrade pump performance and coolant supply can be detected with a flow transducer. As long as the flow transducer detects coolant flow within allowable tolerances, the output signal will remain high permitting beam start-up and operation.

Pressure differential across the pumps would also be an indicator of a loss in pump performance. Figure 5 shows an example target cooling system, and includes a differential pressure device across the parallel combination of the three primary coolant pumps. It may be more desirable to install a differential pressure device across each pump to provide specific information on individual pump performance. The addition of a pressure sensor in the primary coolant loop could be used to indicate loss of pressure and provide a beam shut down signal. Again, the logic would be to allow a run permit (beam on) only if the pressure across the pump exceeds some high fraction (perhaps 90%) of that expected under full pumping conditions, or trip if pressure falls below an allowable set point.

Additional confidence and reliability can be achieved as needed or desired by combining the output of the beam trip condition detection systems in a two-out-of-four voting logic system to execute the trip function. This system allows for high reliability of the shut down function and high protection against spurious trips.

VII. SUMMARY AND CONCLUSION

In principle, it should be easier to operate even large accelerator-driven target systems more safely than it would be for comparable (total neutron production) nuclear reactors. The spallation target operates at lower power (the energy released per neutron produced is less), poses much smaller radiological hazards, and builds up much lower levels of after-heat.

Additionally, there are many ways to shut down an accelerator quickly and reliably, and without relying on "moving components", like control rods. However there exists a niche in safety space that needs to be addressed, one that is comparable to the "Anticipated Transient Without Scram (ATWS)" class of reactor accidents. This list includes all initiating events expected at least once in the facility lifetime in combination with an assumed failure to shut off the particle beam that drives the target. While such scenarios are very unlikely, the consequences can develop quickly and be significant, depending on the details of the design.

An interesting option for reducing any vulnerability to this class of events involves examining initiating events of high likelihood and provides a simple, and possibly passive, means of shutting down the beam whenever necessary. An obvious example is the trip of a main coolant pump. If this, in combination with failure to shut down the beam, could lead to significant target damage, then the designer should make it nearly impossible for the accelerator to operate if the pumps are not running. Both passive options and simple active (electronic) options exist for doing so, the only issue is which approach would provide the most reliable beam shut down.

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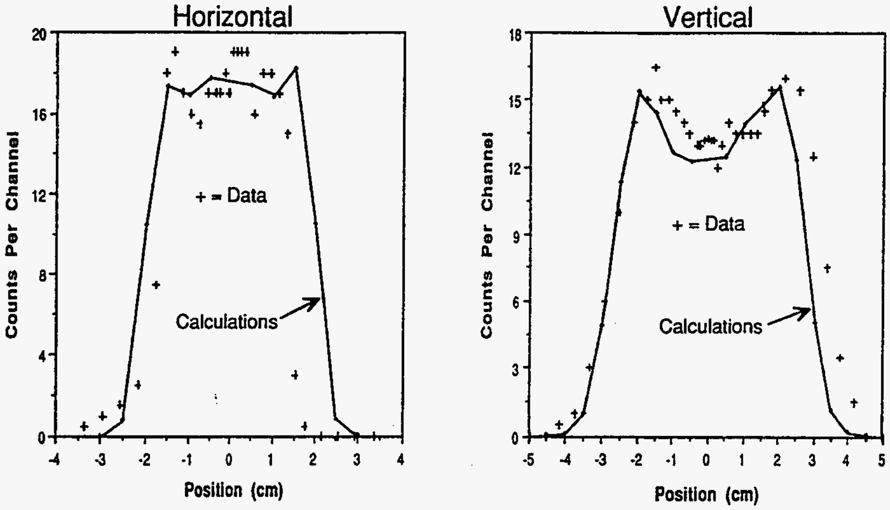
Distribution Of Protons From BNL's Two-Dimensional Beam Expander



Notes: 1) Monte Carlo Calculations and Measurements Subject to Statistical Variations
2) Distribution Is Key Consideration, Alignment and Width Can Be Controlled

Figure 1

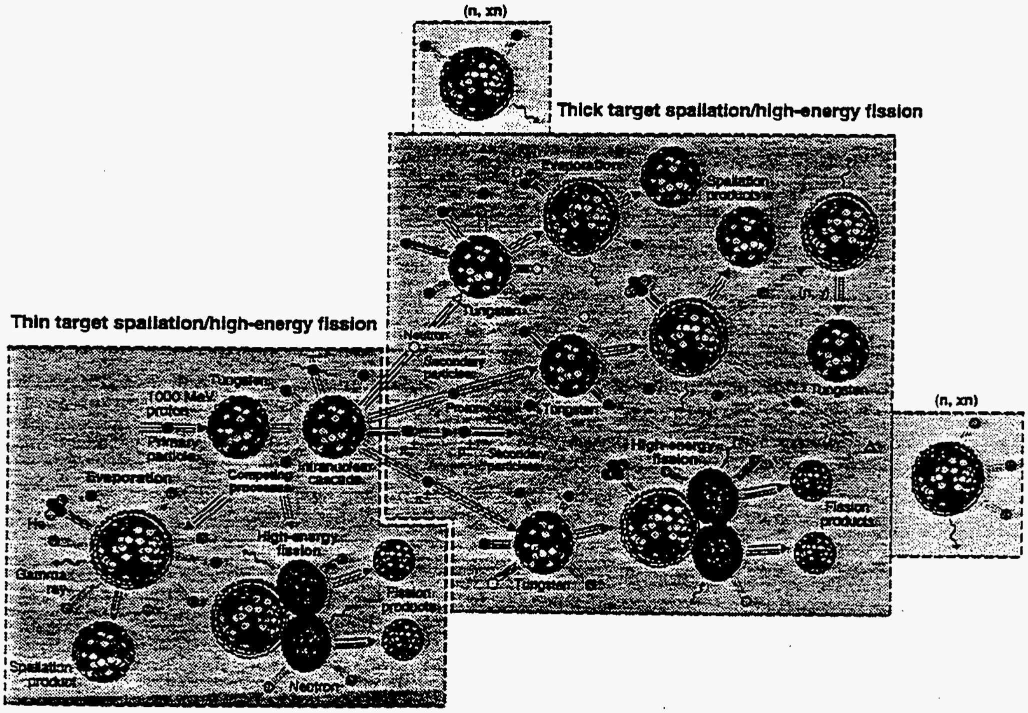


Figure 2. Illustration of the spallation process in thick targets, with evaporation competing with high-energy fission in the de-excitation of highly-excited nuclei.

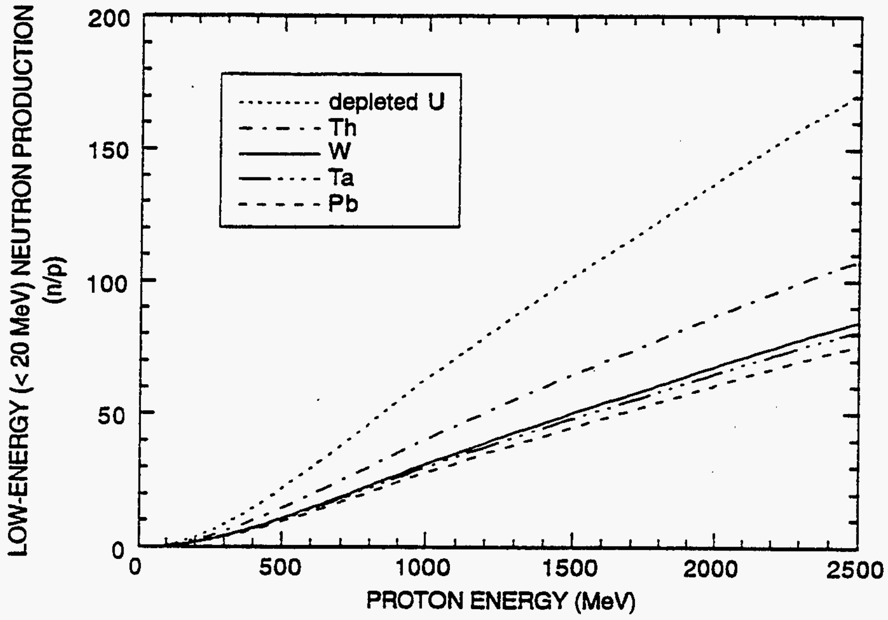


Figure 3. Production of neutrons below 20 MeV per incident proton for 5 target materials.

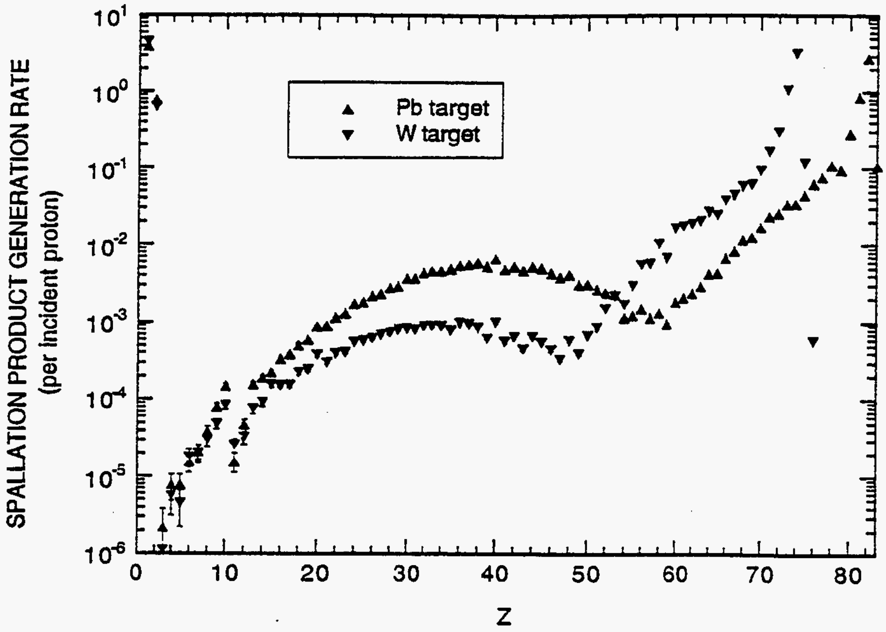


Figure 4. Completed spallation, activation (mostly in tungsten), and fission (mostly in lead) product generation rate for 50-cm-diam 200-cm long lead and tungsten targets bombarded on axis by 1000-MeV protons.

Target Cooling

① --FLOW TRANSDUCER

② --TEMPERATURE TRANSDUCER

③ --PRESSURE TRANSDUCER

④ --COOLANT LEVEL TRANSDUCER

⑤ PRESSURE DIFFERENTIAL

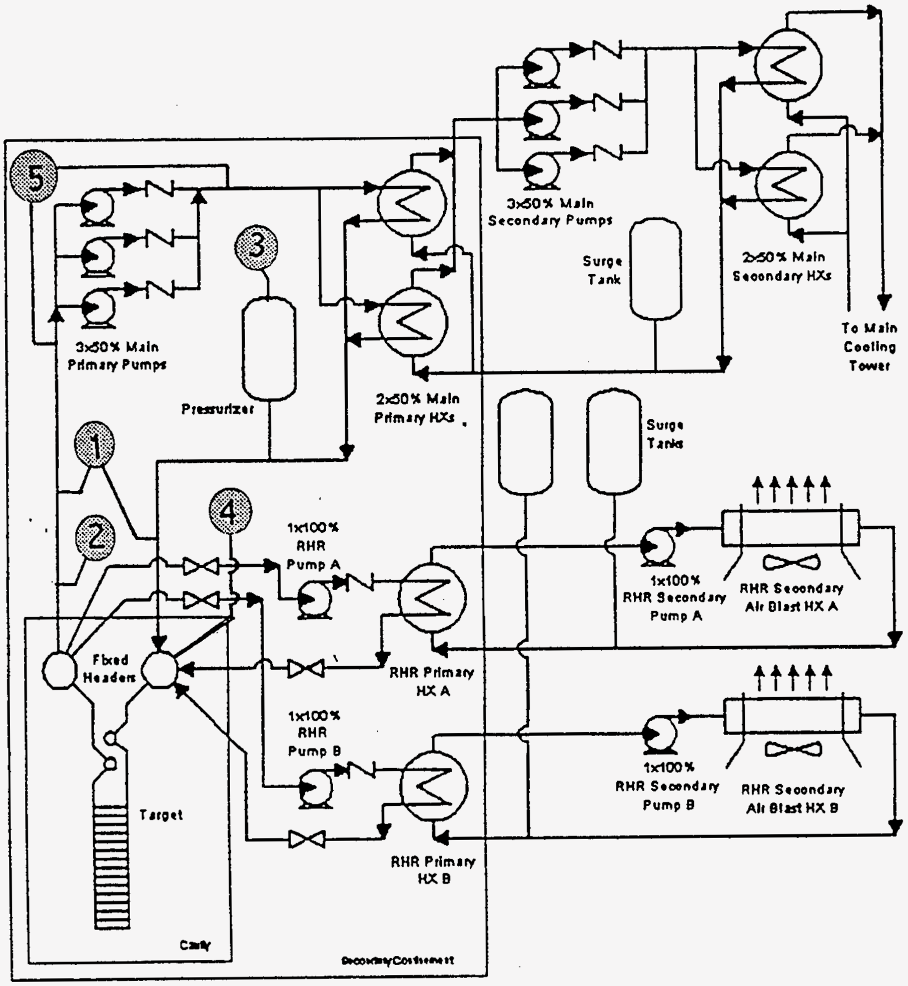


Figure 5

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