NUCLEAR MICRO-REACTOR SHIELDING IMPROVEMENTS SINCE THE 1960s

TR-3B Antigravity Physics Explained

By John Kooiman

"TR-3B Antigravity Physics Explained, insofar as General Relativity can be considered an explanation for gravity."

The TR-3B's propulsion system is as follows: A circular, plasma-filled accelerator ring called the Magnetic Field Disrupter, surrounds the rotatable crew compartment and is far ahead of any imaginable technology... The plasma, mercury-based, is pressurized at 250,000 atmospheres at a temperature of 150 degrees Kelvin, and accelerated to 50,000 rpm to create a super-conductive plasma with the resulting gravity disruption.

The MFD generates a magnetic vortex field, which disrupts or neutralizes the effects of gravity on mass within proximity by 89 percent...

The current MFD in the TR-3B causes the effect of making the vehicle extremely light, and able to outperform and outmaneuver any craft, yet the performance is limited only by the stresses that the human pilots can endure. Which is a lot, really, considering along with the 89% reduction in mass, the G forces are also reduced by 89%. The crew of the TR-3B should be able to comfortably take up to 40Gs... Reduced by 89%, the occupants would feel about 4.2 Gs. The TR-3B's propulsion is provided by 3 multimode thrusters mounted at each bottom corner of the triangular platform. The TR-3 is a sub-Mach 9 vehicle until it reaches altitudes above l20,000 feet - then who knows how fast it can go

The charged particles of the plasma don't just spin uniformly around the ring, but they tend to take up a synchronized, tightly pitched, helical (screw thread) motion as they move around the ring. This can be understood in a general way as follows: the charged particles moving around the ring act as a current that in

turn sets up a magnetic field around the ring. It is a well-known fact that electrons (or ions) tend to move in a helical fashion around magnetic field lines. Although it is a highly complex interaction, it only requires a small leap of faith to believe that the end result of these interactions between the moving charged particles (current) and associated magnetic fields results in the helical motion described above. In other words, the charged particles end up moving in very much the same pattern as the current on a wire tightly wound around a toroidal core.

The TR-3B utilizes a little-known loophole in General Relativity Theory to create its antigravity effects! Even though the TR-3B can only supposedly cancel 89% of gravity (and inertia) today, there is no reason why the technology can't be improved to exceed 100% and achieve true antigravity capability!

The requirement for a dense material moving at relativistic speeds would explain the use of Mercury plasma (heavy ions). If the plasma really spins at 50,000 RPM and the Mercury ions are also moving in a tight-pitched spiral, then the individual ions would be moving probably hundreds, perhaps thousands of times faster than the bulk plasma spin, in order to execute their "screw thread" motions. It is quite conceivable that the ions could be accelerated to relativistic speeds in this manner.

The Materials Behind a Submarine's Nuclear Reactor

Using nuclear fission as a method of propulsion has been researched and developed since the early 20th century. From the moment the first nuclear submarine, the USS Nautilus, was commissioned in 1954 by the US Navy, the concept proved its potential, achieving feats of sustained speed and time submerged that no other conventional submarine of its time could hope to match.

Such achievements would not have been possible without the power of nuclear fission and the material science used to harness it safely. This article will analyze the materials used in a modern-day reactor of a 2018 HMS Astute submarine, to highlight the material science required to make this technology a reality.

How Nuclear Fission Works

To understand why certain materials are chosen for nuclear reactors, an explanation for how nuclear reactors work is required.

Nuclear reactors are powered by a process called nuclear fission, in which a neutron is fired into the nucleus of a 'heavy' atom, causing it to become unstable and split. This releases energy as heat and other neutrons absorbed by other atoms, repeating the cycle. Released energy heats surrounding water into steam. At this point, the reactor acts essentially as a steam engine. The steam turns a turbine (in this case, propelling the submarine), before being condensed back into water and sent back to the reactor's core.

The HMS Astute uses a Pressurized Water Reactor (PWR), instead of a Boiling Water Reactor (BWR). A PWR has two water circuits. The reactor core heats up the highly pressurized primary circuit. Despite being heated beyond its typical boiling point, the tremendous pressure keeps the water in its liquid form, known as 'super-heated water'. The secondary circuit heats and converts into steam by this primary circuit. However, a BWR only has a single circuit. This explanation provides an insight into the extreme conditions that these reactors are required to withstand.

The Outer Layers of The Reactor (Vessel and Shielding)

The vessel of the reactor is the component that houses the core itself. This vessel undergoes some of the most extreme conditions in the entire reactor: it must withstand extremely high temperature and pressure, while continually being struck by stray neutrons from the fission process within. Its material must be exceedingly robust so that it does not suffer any cracks or other significant structural failures. If this structure is compromised, nuclear radiation would be released into the environment. In a space as enclosed as a submarine, such a scenario would be hazardous.

Engineers use specifically treated materials to create the vessel. In the case of the HMS Astute, a low alloy manganese molybdenum steel is used. The manganese and molybdenum content significantly improves the steel's mechanical properties such as strength.

The alloy is also highly weldable, which is a desirable characteristic, as welding is the process of choice when creating vessels. Welding is better at handling large loads than most other joining methods as it distributes the load more evenly, minimizing singular points of high stress.

The alloy is also resistant to neutron irradiation, which typically causes materials to become brittle, deteriorating both its weldability and toughness. The material is usually quenched and tempered, further improving its strength.

Around the vessel is further shielding, to lower the number of neutrons and gamma rays that may escape. The HMS Astute reactor has two primary shields. The lower half comprises a solid-immovable lead tank of freshwater, which absorbs most gamma rays. Hydrogen in fresh (light) water has a relatively high absorption cross-section, as it can form deuterium. Water is also a good moderator as it reduces the high energy of neutrons moving through it, reducing their speed.

The upper half of the shielding is flexible, as it is made of many large blocks of polyethylene. Like light water, polyethylene has a very high hydrogen content, giving it a high absorption cross-section. Similarly, its scattering power - the ability to reduce an incoming neutrons energy - is considerably increased. The upper primary shielding must be movable, as engineers will insert fuel and boron control rods into the vessel via a removable top.

Inside the Core (Fuel Rods, Control Rods, and Moderator)

Within the core, there are fuel rods filled with radioactive pellets. Most commonly, these pellets are made of enriched uranium dioxide, which is made into a powder and then turned into small ceramic-like pellets using high pressure and heating (a process known as sintering).

The HMS Astute fuel pellets are filled with helium to better transfer heat and prevent overheating. It also contains clad in a corrosion-resistant alloy with a low neutron absorption rate so that it does not absorb the outgoing neutrons and prevent the fission process.

Enrichment of the uranium dioxide refers to a process that increases the percentage of the U-235 isotope. Natural uranium typically has around 0.7% U-235. The rest of its content is the non-fissile U-238 isotope. Enrichment can increase this percentage to as high as 5%, making it much more efficient in undergoing fission.

Nuclear fission, if not properly controlled, will grow exponentially; one neutron can split an atom and release two neutrons. This growth has the potential to meltdown or even explode a reactor’s core. Many control rods are placed between the fuel rods to prevent this, and can be dropped in at any time to stop the fission process.

Control rods are usually made of boron, as it has a high neutron absorption rate and a high melting point. Furthermore, the reactor's temperature is moderated by using the primary circuit’s water as a coolant. The water also acts as a moderator, lowering the neutron’s speed to increase the likelihood of a collision occurring, instigating a fission reaction.

With these materials together, the HMS Astute is capable of propulsion from one of the most efficient energy sources currently known. As propulsion and energy methods progress, material science adapts to make them possible, and the scientific feat of the nuclear reactor is no exception.

Shielding Development for Nuclear Thermal Propulsion Jarvis A. Caffrey1,2 , Carlos F. Gomez2, Luke L. Scharber2 1Department of Nuclear Engineering & Radiation Health Physics, Oregon State University, Corvallis, OR 97301 2NASA Marshall Space Flight Center, Huntsville, AL 35812 541-227-4295; jarvis.a.caffrey@nasa.gov Abstract. Radiation shielding analysis and development for the Nuclear Cryogenic Propulsion Stage (NCPS) effort is currently in progress and preliminary results have enabled consideration for critical interfaces in the reactor and propulsion stage systems. Early analyses have highlighted a number of engineering constraints, challenges, and possible mitigating solutions. Performance constraints include permissible crew dose rates (shared with expected cosmic ray dose), radiation heating flux into cryogenic propellant, and material radiation damage in critical components. Design strategies in staging can serve to reduce radiation scatter and enhance the effectiveness of inherent shielding within the spacecraft while minimizing the required mass of shielding in the reactor system. Within the reactor system, shield design is further constrained by the need for active cooling with minimal radiation streaming through flow channels. Material selection and thermal design must maximize the reliability of the shield to survive the extreme environment through a long duration mission with multiple engine restarts. A discussion of these challenges and relevant design strategies are provided for the mitigation of radiation in nuclear thermal propulsion. Keywords: NTP, shielding, radiation, dose, heating INTRODUCTION Nuclear thermal propulsion (NTP) systems provide a dramatic improvement in performance for missions requiring both high thrust and high specific impulse, namely long duration crewed exploration missions. NTP systems can increase cargo capacity and reduce the time spent in extraplanetary space, both of which will serve to reduce overall mission risk and cosmic radiation exposure. However, NTP systems present a number of additional challenges beyond those of non-nuclear propulsion, including the need to mitigate radiation generated by nuclear fission. The growing concern of long duration exposure to cosmic radiation has now brought a great deal of focus on mitigating radiation risk in crew compartment design and material selection. In light of this growing concern for a crewed Mars mission, it is now pertinent to re-approach the problem of shielding and radiation mitigation for a nuclear thermal propulsion stage. SHIELDING CHALLENGES Reactor shield design should, for any reactor, be intimately involved in system design from its earliest stages. Penetrating radiation tends to produce system interfaces in otherwise unrelated components. Beyond the obvious health protective requirements, radiation shields serve vital roles to minimize unwanted radiation heating and reduce degradation of electronic and mechanical components. The process of absorbing radiation energy yields heat that must be managed in some fashion, and the shields must be able to perform reliably in the face of thermal stress and high levels of radiation exposure. Performances Requirements Radiation shields must be designed to meet some given performance requirement. In terrestrial reactors, this is often defined by the need to minimize the ambient dose rate at a given location or the need to minimize radiation damage to the reactor pressure vessel. In the case of nuclear thermal propulsion there are three possible limiting requirements for a shield design. First, and most obvious, is the desire to minimize radiation dose to the crew. Second, heating in the propellant must be minimized to avoid localized boiling and pump cavitation during engine operation. Third, material damage to critical components must be held within their rated exposure limits. Dose to Crew Health physicists apply the principle of ALARA, or As Low As Reasonably Achievable, in common practice. An emphasis is often given to the 'Reasonable' aspect of this approach, where the benefits of lower doses must be balanced against other factors such as cost, weight, and complexity. Likewise, radiation dose to personnel in or near a nuclear propelled spacecraft should be minimized to the greatest extent possible, within reason. It must be held in perspective that the doses received by astronauts on a long term expedition outside of Earth's protective magnetic field, while still largely unknown, could certainly exceed a full Sievert (Sv) (recall that 1 Sv = 100 rem) over the course of a mission due to the pervasive galactic cosmic rays (GCR) and sporadic solar particle events (SPE). Even rudimentary shielding of a nuclear engine, combined with the inherent shielding provided by the spacecraft and cargo, would likely reduce accumulated reactor-produced dose levels to an order of magnitude less than the space radiation dose. In any case, crew dose limits for space exploration missions are not yet fully defined, however a set of guidelines for short term and deterministic effects (Table 1) and long term stochastic effects (Table 2) were recently provided in a NASA Standard [1]. TABLE 1. Dose limits for Short-Term or Career Non-Cancer Effects (in mGy-Eq. or mGy) [2] Organ 30-day limit 1-year limit Career Lens 1,000 mGy-Eq 2,000 mGy-Eq 4,000 mGy-Eq Skin 1,500 3,000 6,000 BFO 250 500 Not applicable Circulatory system 250 500 1000 CNS 500 mGy 1,000 mGy 1,500 mGy CNS (Z≥10) - 100 mGy 250 mGy TABLE 2. Example effective dose limits for 1-year missions resulting in 3% REID, assuming equal organ dose equivalent for all tissues and no prior occupational radiation exposure [3] Females Males Age (yr) Avg US Adult Population Never-Smoker Avg US Adult Population Never-Smokers 30 0.44 Sv 0.60 Sv 0.63 Sv 0.78 Sv 40 0.48 Sv 0.70 Sv 0.70 Sv 0.88 Sv 50 0.54 Sv 0.82 Sv 0.77 Sv 1.00 Sv 60 0.64 Sv 0.98 Sv 0.90 Sv 1.17 Sv Such limits, when fully defined, will be based upon the combined effects of natural and manmade sources. Limits to radiation exposure from a nuclear engine will then need to be balanced against the anticipated dose received from cosmic rays. In terms of shielding efficiency, then, it makes better sense to allocate mass into combined shielding strategies within the crew compartment that can also serve to minimize dose from solar particles and secondary radiation produced from GCR collisions in the spacecraft. Concepts such as reconfigurable water bladders, food pantries, and waste storage can serve as slab shielding to mitigate radiation from the engines during their short periods of operation and then repurposed into 4π shielding during the long coasting stages where cosmic radiation burdens dominate. This principle does have limitations, however, in that high-Z materials such as lead or tungsten should not be placed near the crew compartment due to the increased production rate of secondary particles produced by GCR spallation. Heating in Propellant Current mission architectures for nuclear thermal propulsion feature cryogenic liquid hydrogen as a propellant due to its low atomic mass that affords the highest possible specific impulse with NERVA-type solid core designs. Liquid hydrogen also serves as a reasonably effective neutron shield, although its low density mandates extremely large storage capacities. Liquid hydrogen must be actively maintained at cryogenic temperatures as heating due to sunlight and cosmic radiation results in boil-off and requires venting to avoid excess pressurization. Absorption of nuclear radiation energy dramatically increases the heating rate within cryogenic propellant, particularly during engine operation. As a simplified example case, consider an unshielded reactor adjacent to a cryogenic storage tank of very large diameter that imposes a geometry factor of one fifth of the 4π solid angle for isotropically emitting radiation. For a reactor operating at 1,000 MW with 0.5 percent of energy leaking by penetrating radiation, the tank will absorb about a full megawatt of thermal energy through nuclear radiation alone. Obviously, even in the absence of a crew or radiation sensitive equipment, shielding is needed to minimize this thermal burden in cryogenic storage. Heating of cryogenic fluid during engine operation is not necessarily undesirable, though. The process of pumping fluid from the storage tank requires that the void space, or ullage, in the tank must be repressurized to maintain a constant pressure at the pump feed line. Likewise, adding thermal energy to the cryogenic fluid will not necessarily increase the system temperature, as the reducing tank pressure caused by pumping will force vaporization accompanied by cooling. From a bulk fluid perspective, then, there is a balance that may be struck between the influx of radiation energy and evaporative cooling due to pumping. In reality, though, most of the radiation is absorbed closest to the reactor. This is particularly the case for neutrons that deposit the majority of their energy within the first centimeters of liquid hydrogen at the aft tank face. The problem, then, is the effect of localized heating in the location likely to be nearest the pump inlet. The resulting effects of localized boiling and pump cavitation would lead to catastrophic failure of the turbopumps. Preventing cavitation will likely be the dominating performance requirement of a reactor shield, and establishment of radiation flux limits in this regard is ongoing. Material Radiation Damage Some components in a nuclear propulsion system may be sensitive to radiation damage, particularly in the case of electronic control circuits and motorized actuators. Extensive work in the field of radiation hardening for aerospace applications (electronics) and terrestrial nuclear applications (pumps, valves, and motors) will provide a wealth of options for system design. It is unlikely, then, that component radiation damage will be the largest driving factor for radiation shield design. Sensitive electronics and other components can be placed within the protection of an existing shield or utilize spot-shielding as needed. A likely candidate for the most sensitive critical component that must be reactor-adjacent is the control drum actuator stepper motor, which will likely need to incorporate an extended coupling shaft that penetrates a layer of shielding. Thermal Performance Radiation shielding located near an operating reactor core will be subjected to a substantial thermal load as radiation energy is converted to heat. The shielding system must maintain temperatures within acceptable limits to maintain structural integrity. In the case of a high power reactor, active cooling is required to counteract this heat generation. If active cooling is provided by coolant flow within the shield, then radiation streaming through those flow channels must be mitigated. Of particular concern is the spatially non-uniform heat generation within the shield, in which those regions closest to the core centerline are subject to heating that is several orders of magnitude greater than elsewhere in the shield. SHIELDING DESCRIPTION The radiation shield system for a nuclear thermal engine needs only to shield the fraction of radiation emitted toward the vehicle and crew. This ‘shadow shielding’ method is possible because of the placement of the engines at the aft of the spacecraft and lack of atmosphere or other matter to facilitate scatter. The shield must be capable of attenuating the substantial source of penetrating gamma rays emitted during engine operation, and, to a lesser extent, the continued emission of gammas from fission product decay and activation. Leakage of neutrons from the core during operation must also be mitigated, particularly for fast neutrons that must be slowed and absorbed. Neutron shielding Neutron shielding typically occurs in multiple stages from the perspective of individual neutrons. First, in the case of a high energy neutron, the kinetic energy must be shed by nuclear collisions. Elastic collisions with heavy nuclei such as lead or tungsten will have little effect on the kinetic energy of the incident neutron due to the conservation of momentum (think of a ping pong ball against a bowling ball). Kinetic energy is more effectively shed by collisions with lighter atoms such as carbon, beryllium, and especially hydrogen. With each scattering collision, the neutron sheds more energy and subsequently increases the chance of absorption in a receptive nucleus. The probability of absorption is typically highest for the lowest energy neutrons, or 'thermal' neutrons in energy equilibrium with the thermal motion of their surrounding atoms. A purely elastic scattering shield, such as beryllium, is not considered effective as the thermal neutrons will exit the shield and be absorbed elsewhere. Thus, the neutron shield needs to both slow and capture the incident neutron flux. Inclusion of nuclides with a high absorption cross section is desirable, but neutron capture typically produces some form of secondary radiation emission. Shields that use absorbers producing high energy gammas must therefore account for a third stage in the neutron shielding process by absorbing these penetrating secondary photons. Gamma shielding Gamma shielding is, by comparison, a much simpler task. Gammas are scattered and absorbed through electron interactions, and are best attenuated by materials with a high charge density (high-Z) such as lead, tungsten, or uranium. In the case of a combined shield in which secondary gammas are produced within the neutron shield, it may seem more efficient to place all of the neutron shield material between the reactor source and the gamma shield so that fission and secondary gammas are all captured in a single layer. This would be true in the case of one-dimensional slabs where the diameter of all shield layers is constant. In a shadow-shield, however, the diameter of the shield is roughly defined by a conical solid angle of a sphere with its origin in the reactor core (in fact, the origin of that sphere would be defined by a distribution extending below the core). The consequence of this geometry is that shield layers further from the source will have a greater diameter and mass. Material Selection Early development in the NERVA program featured a substantial effort in material selection in which a large number of candidate materials were considered, particularly with regard to neutron shielding [4]. Of these, only a handful can be considered viable, and two such materials consistently stand out: lithium hydride and boron carbide. Comparisons of these materials could be made at great length, but for the purposes of this paper are summarized briefly. Lithium hydride (LiH) stands out as the most effective neutron shield material per unit mass, owing to its incorporation of hydrogen as a moderator and as an excellent neutron absorber when enriched in Li-6. Its performance suffers in high-flux environments, however, as its poor thermal conductivity and narrow range of operating temperature make effective cooling strategies nearly impossible. Its reactive nature mandates that it be sealed within some containment, but its large volume expansion in melted liquid phase must be accounted for during casting and after containment closure. Boron carbide (B4C) stands out often as the most effective neutron shield per unit volume, but with a mass penalty in the neutron shield of about 20% greater than that of a practical lithium hydride shield. As a ceramic, B4C has excellent thermal conductivity, hardness, and chemical stability. Although its moderating capacity is reduced by the absence of hydrogen, it does still moderate effectively and absorbs with minimal production of secondary gammas. It is currently manufactured in large quantities at relatively low cost, and although use of enriched boron-10 would increase cost above that of off-the-shelf products, those manufacturing processes would remain unchanged and are readily available. SHIELDING ANALYSIS Shielding design is expected to be a highly iterative process that cycles between efforts in optimizing physical effects in radiation transport and thermal performance while aiming to minimize system mass. Outer iterations in system and stage design will inevitably introduce changes to both the source term within the reactor and to performance constraints such as permissible flux. With that in mind, the best approach is to push forth with a limited set of design constraints and focus upon developing an efficient and repeatable analysis approach. The current state of shielding analysis represents a first pass at this process and the results presented herein are generally derived from non-optimized shielding designs. The processes and tools described will then be implemented within a generalized shield analysis toolkit that will enable rapid optimization based upon constraints fed by reactor design and staging parameters. Monte Carlo Radiation Transport Most results reported here are derived out of Monte Carlo radiation transport calculations in the MCNP6.1 transport code from Los Alamos National Laboratory (LANL) and available through the Radiation Safety Information Computational Center (RSICC) [5]. Source terms were generated in an MCNP6 model of a low-enriched reactor core design featuring tungsten composite fuel and a large fraction of moderating tie-tubes. A broad discussion of techniques relevant to dose and shielding calculations in MCNP are provided in Kiedrowski’s criticality alarm primer [6]. Source Normalization Simulation of reactor criticality in MCNP does not explicitly behave as it would in a true reactor, particularly in terms of treatments for time and power generation. Tally measurements are normalized per neutron generated in the simulation. In order to normalize any results from a simulation to a physical unit of reactor power, the user must determine a normalization constant C that relates the average number of neutrons produced in the reactor per fission, ⍰⍰̄, to the average energy produced per fission, Q, as in Equation (1). ⍰⍰ = $\bar{\nu}\ Q$ (1) It is important to note that that these values may change depending upon fuel selection, neutron energy spectra, core life cycle, and time of reactor operation. In practice, this would be calculated with conversion factors to directly relate the neutron production rate to reactor power in terms of wattage over a given time interval, with an example given in Equation (2). 1 $W \cdot s$(1 J s⁄1W)(1 MeV 1.6E −13J)(1 $Fission$ ~200 MeV)(2.445 $neutrons$ 1 $Fission$ Surface Source Recording) =7.64E10 n $W \cdot s$ (2) MCNP permits the recording of fully characterized radiation tracks passing through a defined surface or produced within a given cell. The user can apply this ‘Surface Source Write’ (SSW) functionality within a criticality calculation to capture the particle fluence exiting the reactor boundaries. With careful consideration, subsequent calculations can utilize the ‘Surface Source Read’ (SSR) functionality to recreate the same radiation environment around the reactor with no need to track the dense population of neutrons within the core. The internal radiation environment would not be expected to change significantly between shielding design iterations, so the SSW/SSR functionality provides orders of magnitude in time savings for shielding design analysis.

Variance Reduction Reactor shielding problems are notoriously difficult to perform in Monte Carlo analysis. The nature of a successful shield means that the total number of particles exiting the shield system is vastly lower than those entering the system, typically by many orders of magnitude. This means that out of all of the particle histories followed by the computer code, only an extremely small fraction will contribute to the scoring tallies of interest. In order to achieve reasonable statistics within those tallies, either an astronomical number of total histories must be run, or some form of variance reduction must be applied to the system. A number of such techniques were applied in these analyses, including cell importance weighting, weight windows, energy splitting, and DXTRAN, although not all concurrently. A full description of variance reduction techniques is well outside the scope of this paper, but interested readers are encouraged to consult the MCNP user's manual [7]. Time Dependent Dose Calculation Dose rates at the crew compartment vary continuously over the duration of the mission, either through loss of shielding afforded by propellant while the engine is in operation or through the decay of fission products after engine shutdown. The time dependent behavior of dose rates in a nuclear propulsion system are of vital concern, particularly as the propellant is drained near the end of the final burn and dose rates reach a maximum before final engine cutoff. Time dependent dose rates have been modelled in MCNP by varying the propellant load within tanks of the anticipated size and shape for the current reference Mars mission profile. As could be expected, dose rates follow an exponentially increasing curve as the effective shielding thickness of propellant decreases. Gamma dose rates deviate from this trend only at points associated with the transition between stage tanks, where the geometry of the tank ends modifies the rate of change for effective shield thickness under constant flow rate conditions as seen in Figure (1a). The system can be modeled with reasonable accuracy by applying an empirical exponential function in which the dose rate is a function of remaining propellant. Alternatively, a logarithmic interpolation between the data points from the MCNP analysis can help to refine a solution. 1E-2 1E-3 1E-4 Dose Rate (Sv/s) 1E-5 1E-6 1E-7 1E-8 0E+0 5E+2 1E+3 2E+3 2E+3 3E+3 3E+3 4E+3 a) Remaining Burn Time (s) 0E+0 b) 1E+7 2E+7 3E+7 Remaining Propellant Mass (g) 4E+7 1E-23 1E-24 1E-25 1E-26 1E-27 1E-28 1E-29 1E-30 Dose per Particle Emitted (Sv) FIGURE 1. (a) Prompt dose rate during engine operation as a function of remaining burn time. (b) Dose per emitted particle for gamma rays of varying energy groups generated within the reactor core as a function of remaining propellant mass. The abscissae can be considered interchangeable, related by the total mass flow rate of propellant during operation. Contributions to dose from delayed gammas due to buildup and decay of fission products are rather more complex and require a different approach. In one such approach, instantaneous dose rates are calculated for each of six energy groups introduced as a fixed source into the core based upon the power profile determined from analysis of the criticality run. Dose contributions are then determined per emitted particle within a series of photon energy groups. Equation (3) is used to determine energy emission rate by a set of Nj multi-exponential empirical formulas for each energy group j with varying production coefficients αij and accompanying effective half-lives λij, based upon the reactor operating time to and subsequent shutdown time ts assuming a constant fission rate Po , the behavior of which is shown in Figure (2) [8,9,10]. ��j $\Gamma j(to, ts)$ = $Po \sum \alpha ij$ λij i=1 (3) ��$-\lambda ijts$[1 − $e-\lambda ijto$] Thus, a set of six delayed gamma terms and one fission term are used to create a series of expected instantaneous dose rate contributions at discrete propellant loads. These seven terms are combined within a purpose-built MATLAB code to analyze the dose rate throughout the mission, as shown in Figure (3). The simplified model of operation uses two conditions for calculation at discretized time steps. In the 'Engines On' condition, propellant is expended and all instantaneous dose rate components increase as the effective thickness of propellant shielding is eliminated. The fission source term is applied throughout this condition, and buildup of delayed gamma sources from fission products is added as an independent source term. In the 'Engines Off' condition, the fission source is turned off and propellant load is assumed to be static while the delayed gamma term ceases buildup and the existing inventory decays for the remainder of the calculation. Subsequent engine cycles repeat this process and all delayed gamma terms are added to the inventory built-in during the preceding runs. In the current model, no accounting is included for engine transients (startup and shutdown) and no consideration is made for absorption in fission products or bremsstrahlung from beta decay. 1E+20 Energy Emission Rate (MeV/s) a) 1E+19 1E+18 1E+17 1E+0 0-1 1-2 2-3 3-4 4-5 5-7.5 1E+2 1E+4 Time after startup (s) 1E+6 1E+8 1E+20 1E+18 0-1 1-2 2-3 3-4 4-5 5-7.5 1E+0 b) 1E+2 1E+4 1E+6 Time after shutdown (s) 1E+16 1E+14 1E+12 1E+10 1E+8 1E+8 Energy Emission Rate (MeV/s) FIGURE 2. (a) Energy emission rate of fission products across 6 energy groups (labeled in MeV) building in during steady state operation at 560 MW. (b) Energy emission rate of fission products decaying after one hour of operation at 560 MW. The upcoming model will instead use the CINDER-90 algorithm included within MCNP6 to track decay of fission and activation products. Tallies must then be discretized in time, with the resulting time-dependent distribution representing the energy release and absorption behavior after a single fission event. Further processing then yields the relevant values needed to account for source buildup and decay based upon reactor power history. Either of these methods permits flexible integration over user-defined time intervals to determine accumulated dose. FIGURE 3. Example dose rate history calculated in the custom MATLAB code for a reactor operating at 560 MWwith a basic LiH/Pb shield. Isodose and Isoflux Contours Early studies for component selection, sizing, and configuration in a nuclear propulsion system require a basic understanding of the radiation environment presented during engine operation. Contour plots of anticipated radiation levels are especially useful in these early phases to provide guidance for placement of sensitive components and enable simple trades between materials and cost factors. MCNP features a simple implementation of FMESH superimposed tallies that can produce spatial flux distributions. In core-centered analyses, an axisymmetric cylindrical tally is generated about the core centerline. Simple flux (F4-type) tallies may be used for flux measurements, as is often the case for neutrons separated by energy groups, however it is generally more desirable to represent these values in terms of their dose. Energy dependent dose-response factors are then applied as an FM multiplier using log-interpolated interaction coefficients, as in the left side of Figure (4) for photon dose to silicon [8]. Where crew dose is a concern, conversion coefficients were applied for ambient deep dose equivalent from neutrons and photons [11]. Silicon dose rate and neutron fast flux values are shown in Figure (4) for a reactor operating at 560 MW. Alternative representations may instead be normalized to dose/fluence per fission, dose rate/flux per $W \cdot s$, or integrated over the reactor power history to provide total dose/fluence. FIGURE 4. Dose rate in silicon (left) and neutron fast flux (right) profiles for a reactor operating at 560 MW with a basic LiH/Pb shield. Thermal Analysis Substantial heating occurs within the shield due to radiation absorption and collision processes. Bulk heating within individual cells can be calculated easily in MCNP using F6 heating tallies, which can be useful in many respects, but rigorous thermal analysis requires more detailed spatial representation of heating. Segmentation of large cells into smaller component cells is a possible solution, but such an approach is tedious and unnecessary. Instead, as in the case of dose/flux mapping, FMESH superimposed tallies can be used to resolve the spatial effects of radiation heating. An FM multiplier can be used to extract the ENDF energy dependent heating values for specified materials within a given FMESH tally. Heating mesh tallies were generated for simple representative designs featuring boron carbide neutron shield material, assumed as a pebble bed design with bulk material density adjusted to account for effective packing density. Lithium hydride was also considered earlier in the study, but brief analysis suggested that a simple cooling channel model would be inadequate to maintain sufficiently low temperatures near the reactor face and simultaneously maintain sufficiently high temperatures throughout the rest of the shield, as is needed in the case of lithium hydride. Further analysis of lithium hydride was set aside, then, in favor of advancing the more resilient boron carbide design. Lithium hydride will likely be considered in later analyses as part of a multicomponent neutron shield to mitigate fast neutron leakage, as its poor conductivity precludes its use in locations immediately adjacent to reactor components. FIGURE 5. Hydrogen propellant temperature (°C) (assumed equal to pellet surface temperature) in a boron carbide pebble bed shield for a reactor operating at 560 MW after 50 seconds. Effective packing density of 0.6 assumed. As a ceramic, boron carbide features excellent thermal conductivity and very high high temperature limits. Its hardness and chemical stability also permit more construction options. An enticing option is the use of a pebble bed design that allows generous cooling flow while minimizing radiation streaming paths. Pebble beds may also allow for ample opportunity to mix flow streams from multiple inlets prior to injection into the core. One concern for this option, however, was the magnitude of pressure drop across the shield and its negative impact on engine system power balance. That concern was abated in analysis, though, as pressure drop for a reasonable pellet diameter of 2 cm was determined to be no more than 37 kPa (5.6 psi) using the Ergun formulation as in Equation (4), and likely on the order of 15 kPa (2.2 psi) determined by Ergun formulation including the Forcheimer drag term as in Equation (5). Each equation accounts for dynamic viscosity μ, density ρ, fluid velocity V across the flow length of the shield L. In the case of Equation (5), sphere diameter D and porosity ϵ are coupled as permeability k given in Equation (6), and effects of sphere diameter on pressure drop in either case are shown in Figure (6) based upon input assumptions derived from early power balance analysis. ΔP =$150\mu VsL$ $D2$ ΔP =μVsL k 400 350 300 Delta P [kPa] 250 200 150 100 50 0 (1 −ε)2 ε2 +1.75$\rho V2$ D (1 −ε) ε3 +1.75$\rho V2L$ $\sqrt{k}$ k = $D2\varepsilon2$ 150(1−ε)2 ε $\sqrt{150\varepsilon 3}$ Ergun Forcheimer (4) (5) (6) 0 1 2 3 Pellet Diameter [cm] 4 5 FIGURE 6. Pressure drop for gaseous hydrogen in a half-meter length pebble bed shield. Reference reactor operating at 560 MW with effective packing density of 0.6 assumed. Mass Optimization Given a source term and a limit for exiting radiation flux, the problem of shield optimization can be made relatively straight-forward. In the absence of such well-defined limits, the problem becomes more complex. Rather than optimizing to a single point constraint, the system must be optimized in parallel for a distribution of possible performance constraints. As an example in Figure (7), a limited set of various combinations of gamma shield thickness, neutron shield thickness, and gamma shield position are plotted in terms of total mass versus dose rate. The figure demonstrates the optimal curve, or 'Pareto front', for design variables that balance dose rate against shield mass. Points that plot farther from the optimal curve are considered dominated solutions that represent non-optimal designs. Eliminating all but those non-dominated solutions results in the 'Pareto set' of optimal solutions along the Pareto front. Selection of a point design can then be made with constrained minimization once outer constraints are established. For example, if setting a maximum terminal dose rate of 8E-13 $Sv\ s{-}1W{-}1$ for the scenario in Figure (7), then selecting the mass-minimized point design below that point will result in a shield mass of 1,000 kg. 2E-12 Terminal Dose Rate (Sv/s.W) 1E-12 1E-12 1E-12 1E-12 1E-12 9E-13 8E-13 7E-13 6E-13 5E+5 7E+5 9E+5 1E+6 1E+6 Mass (g) 2E+6 2E+6 2E+6 FIGURE 7. Example Pareto optimization plot for various shield designs. Points adjacent to the Pareto front represent optimal, or non-dominated, solutions. OTHER MITIGATION STRATEGIES Engine Placement Standard practices of radiation protection focus upon three factors: time, distance, and shielding. In the case of a nuclear propulsion vehicle, time of exposure is already minimized by mission planning due to other inherent risks of long-duration spaceflight (including cosmic radiation exposure). Shielding is effective, but massive and costly. Distance, however, could be incorporated into a vehicle design to maximize the separation between the crew and the radiation source. For point-sources of radiation (or approximations thereof), intensity is inversely proportional to the square of distance. The current mission architecture is based upon a long-cylinder shape that houses crew opposite the engine assembly, separated by around 80 meters of propellant tanks, structure, and void space. While the length of the spacecraft may seem sufficient to minimize dose, it's important to note that a substantial portion of the radiation reaching the crew compartment is contributed by scatter in the tank assembly near the engines. Heating in propellant near the engines is also likely to be the constraining factor if it is assumed that crew will be otherwise adequately shielded against cosmic radiation. Distancing the reactor assembly away from the bottom face of the tank benefits the system in two ways. First, the added distance reduces the unshielded radiation exposure and thus reduces the required shield thickness to meet a given flux constraint. Second, the added distance narrows the fractional solid angle extending between the source and the propellant tank face, thus reducing the required diameter of the shadow-shield and significantly reduce the required shielding mass. A series of viable truss designs were analyzed in order to validate the feasibility of using a distance truss in place of shielding. Each design type was tested against a maximum thrust loading of 75,000 lbf at a maximum expected gimbal angle of 5 degrees, with lengths varying between 4 and 10 meters. For each case, the minimum required mass was determined. From this process, the most mass-efficient design was selected, shown in Figure (7a) and represented in Figure (8b), assuming construction out of Al-Mg alloy 5454. From this analysis, a polynomial expression for mass was determined as a function of length. Maximum instantaneous crew gamma dose rates were calculated at varying distances from the propellant tank using an internal shield reference design mass of approximately one metric ton. To compare mass effectiveness of additional shielding versus that of a distance truss, a set of optimally located external disk shields of varying mass were placed between the propellant tank and engine, which was anchored at the nominal three meter distance. Figure (7b) displays the dose reduction factor, here defined as the nominal dose rate (3m, no external shield) divided over the point dose rate determined with added shield mass or with added distance in terms of truss mass. a) 4 Dose Reduction Factor b) 3 2 1 0 2 4 Distance Truss External Shield 6 Mass Addition (MT) 8 10 FIGURE 7. a) Buckling analysis of 10m truss determined as mass-optimal for given loading parameters. b) Comparison of gamma dose reduction factors gained by either adding Tank and Stage Considerations Careful planning of stage design with consideration for radiation effects will be necessary to minimize shielding mass. Earlier plans for the NERVA-powered nuclear shuttle implemented conical propellant storage tanks that minimized the exposed geometry, similar to that shown in Figure (8d). This served to reduce scatter source terms and propellant heating, and also improved terminal dose rates as the tank emptied by draining from a narrower column and thus increasing the effective thickness per unit mass of propellant acting as a shield. Some alternative considerations for mitigating dose effects and propellant heating also warrant investigation, including use of a smaller secondary tank, as in Figure (8c) with line routing schemes that prevent pump induction of heated propellant. Benefits of these design considerations must be weighed against other factors, such as cost, reliability, and payload envelope size. a) b) c) d) FIGURE 8. Comparison of various staging design options to mitigate radiation effects. a) Nominal core stage design. b) Distance truss. c) Thermal buffering tank. d) Conical core stage tank. CONCLUSION Development of radiation shielding for a nuclear thermal propulsion stage has progressed considerably in this preliminary design phase. Methods for dose and heating calculations have been refined throughout the project and continue to progress. Upcoming source terms will feature a more rigorous method of decay and activation source production using CINDER-90 production models. Thermal analysis has indicated the feasibility of implementing a pebble-bed type shield using boron carbide, and a framework has been established to quickly iterate shield designs between radiation transport and thermal analysis. Preliminary designs for a distance truss have indicated a tremendously favorable mass trade for radiation effects compared to added mass of external shielding. Boron carbide has been selected as a favorable material for neutron shielding, owing to its low cost of development and improved reliability compared to other materials. Pareto optimization techniques are in use to establish a broad range of mass optimized shield designs, and required constraints for propellant heating to prevent cavitation and boiling are currently being developed. ACKNOWLEDGMENTS Special thanks are extended to Omar Mireles and Daniel Cavender of NASA Marshall Space Flight Center for their guidance in project integration, and to Wesley Deason and Michael Eades for providing interfaces with reactor design. REFERENCES [1] NASA Space Flight Human-System Standard Volume 1, Revision A: Crew Health (NASA-STD-3001). [2] National Council on Radiation Protection and Measurements. Recommendations of Dose Limits for Low Earth Orbit. NCRP Report 132, Bethesda MD (2000). [3] Cucinotta, FA, Kim, M-H, Chappell, LJ. “Space Radiation Cancer

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Nuclear Submarine Radiation Considered in Shielding

Radiation Considered in Shielding

Radiation is all around us. Sources of radiation can be divided into two major categories: natural and man- made radiation sources. Natural sources of radiation include cosmic, terrestrial, and background radiation. The very ground we walk and build our homes on contain radioactive elements that decay in radon gas. Low levels of uranium, thorium, and their decay products are found everywhere. These are ingested with food and water, while others, such as radon, are inhaled. The sun is a source of cosmic radiation, but the earth's atmosphere helps absorb most of the gamma rays and protects us from high doses of cosmic radiation. [4] Internally, K-40, C-14, and tritium are found inside us from birth. We are also exposed to man-made sources of radiation. Man-made radiation sources are divided into those that the public is exposed to and those that are as a result of occupational exposure. [4] The public is exposed to radiation from tobacco, television, medical x-rays, smoke detectors, nuclear medicine, and building materials. Isotopes from these sources are I-131, Tc-99, Co-60, Ir-192, and Cs-137.

As you can see from the examples above there are many sources of radiation. Clothing or the buildings we work in shield some types of radiation, but there are certain types of radiation that are ore commonly considered when designing radiation shielding. These include neutron sources, gamma photons, and x-rays. Radiation shielding specialists control the many sources of radiation, protect people, and radiation sensitive systems from radiation. The first task to designing radiation shielding is to identify the type of radiation involved, the energy distribution, and strength of the source. [5] Another consideration in radiation shielding is the size of the space allotted for the shield. Due to lack of information about the source of the radiation field, shield designers often only use only estimates or approximations of the radiation field based on their knowledge.

Neutron sources include fission neutrons, photoneutrons, and neutrons from (α, n) reactions. Fission neutrons are important in shield design because they pose biological and radiation damage. [5] Most heavy nuclides will fission on the adsorption of a neutron producing energetic fission neutrons. The fission neutrons, in turn, may produce secondary radiation sources such as inelastic scattering, capture gamma protons, or turn stable isotopes into radioactive isotopes. [5] Fission species include U-235, U-233, U-238, Pu-239, and Th-232. A gamma photon with energy to overcome the neutron binding energy of about 7 MeV may cause (γ, n) reaction, however, most gamma photons have insufficient energy to overcome the binding energy. A few nuclides for photoneutron production are H-2, Li-6, Li-7, Be-9, and C-13. Capture gamma photons from neutron adsorption have the necessary energy (~7 MeV) and can cause production of energetic photoneutrons. [5] Laboratory neutron sources use energetic alpha particles from radioisotopes to induce (α, n) reactions in materials. Most commonly used alpha emitters are actinide elements that form intermetallic compounds with beryllium. This ensures that the emitted particles react quickly with the encounter converter and leakage is minimized. [5] X-rays may be produced from photoelectric adsorption that leaves the adsorbing atom in an ionized state or from the decay of a radionuclide.

Securing Sensitive Spaces: A Look at Nuclear Shielding

January 1, 2025

Building Walls Against Invisible Threats: Technology Shielding Design in Nuclear Facilities

Nuclear power plants and research facilities harness the immense energy locked within atoms, but this power comes with inherent risks. Radiation, both ionizing and non-ionizing, poses a constant threat to human health and the environment. To mitigate these dangers, meticulous engineering goes into every aspect of a nuclear facility, and technology shielding design stands as a critical pillar in ensuring safety.

Understanding the Invisible Enemy:

Radiation manifests in different forms, each requiring specific shielding strategies.

- **Ionizing radiation**, like alpha, beta, and gamma rays, possesses enough energy to strip electrons from atoms, potentially causing DNA damage and leading to cancer or other health issues.
- **Non-ionizing radiation** includes low-energy forms like microwaves and radio waves, which while less potent, can still cause tissue heating and disrupt biological processes over prolonged exposure.

The Shield's Arsenal:

Designing effective shielding involves a deep understanding of these radiation types and their interaction with various materials. The primary shielding materials used in nuclear facilities include:

- **Lead:** Highly dense and effective against gamma rays, lead is commonly used in smaller-scale applications like X-ray machines and radiation therapy equipment.
- **Concrete:** Offers excellent protection against both gamma rays and neutrons, making it a popular choice for building walls and structures within reactor cores.
- **Water:** Its high density and ability to absorb neutrons make water a crucial component of shielding in reactor vessels.
- **Steel:** While less effective than lead or concrete against gamma radiation, steel's strength and durability make it suitable for structural components that require some level of shielding.

Beyond Material Selection:

Effective shielding design goes beyond simply choosing the right materials.

- **Geometry Matters:** The shape and thickness of the shield directly influence its effectiveness. Complex geometries might be needed to precisely target specific radiation sources.
- **Multiple Layers:** Combining different materials in multiple layers can create a more comprehensive shield, maximizing protection against various radiation types.

- **Active Shielding:** In some advanced applications, active shielding systems utilize magnetic fields or particle beams to deflect or absorb radiation in real time.

A Commitment to Safety:

Technology shielding design plays a vital role in ensuring the safety of personnel, the public, and the environment within nuclear facilities. Continuous advancements in materials science and engineering ensure that these protective barriers remain effective against evolving threats, allowing us to harness the power of nuclear energy safely and responsibly.

Real-World Examples: Building Impenetrable Fortresses Against Invisible Threats

The theoretical underpinnings of nuclear shielding are one thing, but witnessing its practical application in the real world paints a vivid picture of its crucial role. Here are some compelling examples demonstrating how technology safeguards us from the invisible dangers of radiation:

US Naval Nuclear-Powered Submarines: Silent, deadly, and incredibly safe: these underwater behemoths rely on powerful nuclear reactors to propel them across vast oceans. The reactor cores are enveloped in multiple layers of shielding – primarily thick steel plates, with water acting as an additional neutron absorber. This complex arrangement ensures that even during a potential accident, radiation remains safely contained within the submarine's hull, protecting the crew and the surrounding marine environment.

Exploring the shielding types used in small modular reactors (SMRs), their effectiveness, challenges, and recent advancements in shielding technologies.

Small Modular Reactors (SMRs) and Shielding: A Comprehensive Overview

Introduction

As the demand for clean and sustainable energy continues to grow, the nuclear industry has responded with the development of small modular reactors (SMRs). These innovative reactors offer a more flexible, scalable, and cost-effective alternative to traditional large-scale nuclear power plants. One of the key challenges in the deployment of SMRs is ensuring adequate shielding to protect both the environment and plant personnel from the harmful effects of ionizing radiation. In this article, we will explore the different types of shielding used in SMRs, their effectiveness, and the challenges faced in their implementation.

What are SMRs?

Small modular reactors (SMRs) are a new generation of nuclear power plants that typically generate between 10 and 300 MWe. Their modular design allows for easier manufacturing, transport, and on-site assembly, resulting in shorter construction timelines and lower upfront capital costs. Moreover, SMRs can be deployed in remote locations, providing electricity to areas that may not have access to large-scale power infrastructure. They are also considered to be inherently safer due to their passive safety features and smaller reactor cores, which produce less decay heat in the event of an accident.

Types of Radiation Shielding in SMRs

There are three primary types of radiation emitted by nuclear reactors: alpha particles, beta particles, and gamma rays. Each type of radiation requires different shielding materials and strategies to effectively protect the environment and personnel from exposure. SMRs, like larger nuclear reactors, utilize various layers of shielding to achieve this goal.

1. Biological Shielding

Biological shielding is the outermost layer of protection in a nuclear reactor, designed to reduce the exposure of personnel to ionizing radiation. This shielding typically consists of concrete, which contains materials such as barium, iron, or other heavy elements to increase its density and radiation absorption capabilities. In SMRs, the thickness of the biological shield may vary depending on the reactor's design and power output. The compact nature of SMRs often requires innovative shielding solutions to maintain a small footprint while still providing adequate protection.

2. Neutron Shielding

Neutrons are uncharged particles released during nuclear fission. They can cause the activation of materials and are harmful to living organisms. Neutron shielding is designed to absorb and slow down these particles, reducing their ability to cause damage. In SMRs, neutron shielding materials may include water, heavy water, or boron-containing compounds, which have a high neutron absorption cross-section. The use of these materials in the reactor's design helps to minimize the production of radioactive isotopes and reduce the radiation dose to personnel.

3. Gamma Shielding

Gamma rays are high-energy electromagnetic radiation that can penetrate deep into materials and cause significant damage to living tissue. Gamma shielding is an essential component of a nuclear reactor's design, as it protects personnel and the environment from this harmful radiation. In SMRs, gamma shielding materials may include lead, steel, or other dense materials that are effective at absorbing gamma rays. The thickness and composition of the gamma shield are determined by the reactor's design and the specific radiation levels produced during operation.

Challenges in Implementing Shielding for SMRs

While SMRs offer many advantages in terms of flexibility and cost, there are unique challenges associated with implementing effective shielding solutions. Some of these challenges include:

1. Space Constraints

One of the primary benefits of SMRs is their compact design, which allows for easier transport and installation. However, this also poses a challenge for incorporating shielding materials, as there is limited space available. Designers must balance the need for adequate shielding with the desire to maintain a small footprint, often requiring innovative approaches and materials to ensure effective radiation protection.

2. Manufacturing and Transport

The modular nature of SMRs requires that shielding components be manufactured off-site and transported to the construction location. This can present logistical challenges, particularly when dealing with heavy and bulky shielding materials like lead or steel. Additionally, ensuring the quality and consistency of shielding materials throughout the manufacturing process is crucial to their effectiveness in protecting against radiation.

3. Regulatory Compliance

As with any nuclear power plant, SMRs must meet strict regulatory requirements to ensure the safety of both plant personnel and the environment. This includes adhering to guidelines for radiation shielding, which may vary depending on the specific design and location of the SMR. Navigating these regulatory requirements can be complex and may necessitate a tailored approach to shielding for each SMR project.

Recent Advances and Future Developments

As the demand for SMRs continues to grow, the industry has responded with new research and advancements in shielding technologies. Some of these recent developments include:

1. Nanotechnology

Researchers are exploring the potential of using nanoparticles to enhance the radiation shielding properties of traditional materials.

By incorporating nanoparticles into shielding materials like concrete or polymers, it may be possible to create more effective and lightweight shielding solutions for SMRs.

2. Advanced Manufacturing Techniques

Advanced manufacturing techniques, such as additive manufacturing or 3D printing, have the potential to revolutionize the production of shielding components. By utilizing these techniques, designers can create custom shielding solutions tailored to the specific needs of each SMR project, while also reducing waste and improving overall efficiency.

3. New Shielding Materials

There is ongoing research into the development of novel shielding materials that can provide enhanced protection against radiation while minimizing weight and space requirements. These materials may include new alloys, composites, or even metamaterials, which are engineered to exhibit unique properties not found in nature.

Conclusion

Effective radiation shielding is a critical aspect of SMR design, ensuring the safety of plant personnel and the environment. Despite the challenges posed by space constraints, manufacturing, and regulatory compliance, advancements in shielding materials and technologies are paving the way for innovative solutions that meet the unique needs of small modular reactors. As the demand for clean, sustainable energy continues to rise, these developments will play a crucial role in the widespread adoption and success of SMRs.

Streaming in a Nuclear-grade Sandwich Composite for Microreactor Shielding

Ryan Stewart, Samuel Bays, Adam Zabriskie, Joshua Zelina, Robert Spears

Abstract

The NGSC is a new approach to develop a shield structure for microreactors which combines the biological shielding with the reactor pressure vessel. Six layers of SS316 skins and core materials are present in the NGSC, where the core materials are reduce the neutron and gamma dose. Previous work has examined how a simplified NGSC can be optimized for cost, dose, and weight. This work explored the inclusion of SS36 ribs, which helps maintain the structural integrity of the NGSC, affects the transportation of radiation through the NGSC. For B$_4$C layers, the addition of ribs reduces neutron absorption but increase photon absorption. For WB$_4$-cermet layers, the addition of ribs reduces neutron absorption and reduces photon absorption.

Progress in Nuclear Energy

The technology of shielding design for nuclear reactor: A review

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Highlights

- Potential shielding materials for neutron and γ-ray are analyzed.
- The hybrid deterministic/Monte Carlo simulation is proposed.
- The technologies of shielding design of nuclear reactor are overviewed.
- Valuable conclusions and suggestions for future work are proposed.

Abstract

The requirements of shielding protection originate from a series of industrial applications, including reactor, storage of spent fuel, radiology, nuclear medicine, etc. In this work, the technologies of reactor shielding are overviewed systematically. Potential shielding materials for neutron and γ-ray are analyzed. Their advantages and disadvantages are outlined. The methods for shielding design and simulation are evaluated. Finally, the hybrid deterministic/Monte Carlo simulation is proposed, especially for the deep penetration in complex geometry. Suggestions for the future work are outlined and analyzed. It is hoped that this work and obtained results will be encouraging to the researchers in their future work.

Introduction

The main radiation products of a nuclear facility include α-particles, β-rays, γ-rays, neutrons, etc. Usually, α-ray and β-ray and can be shielded by a thin sheet, due to their weak penetration, while the shielding of γ-rays and neutrons are much more difficult, caused by their very strong penetration capacities (Song et al., 2021). Therefore, the nuclear shielding design is mainly focused on the protection of γ-rays and neutrons.

In nuclear reactor, the sources of γ-rays mainly include three parts: 1) the primary γ-rays emitted from fission reaction of fuel elements, 2) the primary γ-rays generated from the radioactive decay of nuclides, and 3) the secondary γ-rays emitted from (n, γ) reaction of structures (Ko et al., 2014). The neutrons mainly include the prompt and delayed neutrons generated from nuclear fission.

In engineering application, the requirements of shielding originate not only from the reactor, but also from the storage of spent fuel, radiology, nuclear medicine, etc (Dong et al., 2022). Besides the reactor, spent fuel is also highly radioactive and requires special measures for radiation shielding (Grgic et al., 2022). Since the permanent spent fuel storage is unavailable, two alternative solutions, spent fuel pool and spent fuel dry storage are chosen in industries. In these two methods, the compound requirements of the casks, including mechanics, radiation shielding and passive cooling need to be satisfied.

Besides that, the artificial radiation sources in radiology and nuclear medicine have been present worldwide for peaceful applications. For example, the radiological procedures, which include radiography imaging and computed tomography, usually involve the use of x-ray (Ogundare et al., 2008). While the radiopharmaceutical combined with gamma camera are also introduced for the ailment diagnosis in nuclear medicine. Moreover, the ionizing radiations emitted from specific radioactive isotopes, have been widely utilized in oncology and therapeutic nuclear medicine, for the special treatment of health trauma.

In engineering application, the improvement of radiation protection technology, including the designing and materials, are necessary and encouraging for the active use of ionizing radiation. In this work, the technology of radiation shielding design and simulation is overviewed carefully. The potential materials with high performance in shielding and the designing methods are analyzed. It is hoped that this manuscript and the obtained results will be valuable for the future research.

Section snippets

Importance of shielding materials

The radiation protection materials with high performance are usually needed in industries and different kinds of human activities. In deep space exploration, the requirement for advanced shielding material with lightweight and high performance is urgent, for the purpose of improving the life time of electronic equipment in space environment. In physics, most shielding materials are only suited for some specific forms of radiation, which is due to the interaction of radiation particles with

Shielding materials

The selection of shielding material depends on its attenuation efficiency, cross-section, thermal properties, cost, etc (Zadehrafi et al., 2020). In order to reduce the health hazards of radiation, continuous efforts have been carried out by worldwide researchers to enhance material properties, which have led to the development of new materials in radiation shielding (Kawa et al., 2020). Series of literature have reported these shielding materials, such as polyethylene, boron and

Shielding calculation

Shielding design and simulation play important roles in nuclear engineering. It can be used to optimize the shielding structure of nuclear facilities, evaluate the irradiation damage to components, and simulate the irradiation field surrounding the source. In this process, the numerical simulation with high efficiency and accuracy is indispensable, which can not only save the computational resources significantly but also provide basis and guidance for the design of experimental facilities (

Optimization methods

Shielding design is an important process in nuclear reactor design. In order to effectively shielding fast neutrons and gamma rays, designers need to choose suitable procedures, models and databases, based on the nuclear safety regulations and the reactor structure. Then they should complete the calculation of radioactive sources in the reactor, fuel assemblies, related components and systems. Based on these radioactive sources, the shielding structures for reactor and facilities could be

Discussion

An efficient, compact and lightweight shielding design is of vital importance to nuclear facilities, especially for the space reactors and marine reactors. The former has strict weight limit while the latter has strict space and weight limit. Many pioneers have devoted in this field and have made important achievements. Currently, the technology of reactor shielding design mainly includes the development of shielding materials with superior performances, advanced simulation methods and the

Conclusions

In this review, the technologies of reactor shielding design are discussed. The potential shielding materials and simulation methods in shielding design are evaluated. Suggestions for the future work are outlined and analyzed. Detailed conclusions are listed as follows:

- 1.
  The characteristics of ideal shielding materials includes, excellent shielding performance, small volume, mechanical durability, low specific gravity, long service life, etc.
- 2.
  Due to the differences physical mechanisms, it is

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"Unbreakable Armor for Tomorrow's Nuclear Powerhouses" as Next-Gen Reactors Boast Cutting-Edge Shielding Design to Revolutionize Safety Standards

In a groundbreaking development that could redefine nuclear safety standards, scientists at the University of South China have unveiled innovative algorithms designed to optimize radiation shielding for next-generation nuclear reactors.

Eirwen Williams05/04/202532

IN A NUTSHELL
• 🔬 Scientists at the University of South China have developed innovative algorithms to optimize **radiation shielding** for next-generation nuclear reactors. • 💡 The newly created algorithms, RP-NSGA and RP-MOABC, significantly improve performance by integrating a **reference-point-selection strategy** with established optimization techniques. • 📈 Experiments demonstrated that these algorithms achieve substantial reductions in **volume and weight** compared to traditional methods, enhancing efficiency. • 🌐 The algorithms hold potential for broader applications across various **engineering fields**, addressing multi-objective optimization challenges.

The field of nuclear reactor design is on the cusp of a transformative breakthrough, thanks to the innovative work being conducted by scientists at the NEAL of the University of South China. By developing a novel method for optimizing radiation shielding, these researchers are paving the way for safer and more efficient next-generation nuclear reactors. This bold step addresses the growing demands of new reactor types, including transportable, marine, and space reactors, which require lightweight and compact shielding solutions. The new algorithms, RP-NSGA and RP-MOABC, represent a significant leap forward in overcoming the limitations of conventional design methods.

Breaking Ground: Enhancing Radiation-Shielding Design

Nuclear reactors have long faced challenges in achieving optimal radiation shielding due to the limitations of conventional design methods. Traditional techniques often depend on expert intuition and fail to meet the multi-objective demands of modern reactors. The NEAL research team has tackled this issue head-on by developing algorithms that integrate a sophisticated reference-point-selection strategy with well-established optimization techniques. Using genetic algorithms (NSGA) and artificial bee colony algorithms (MOABC), the team has created a solution that enhances performance and simplifies the complex optimization process.

These algorithms are designed to address multiple objectives, such as minimizing weight and size while maximizing radiation protection. By automating the identification of the best possible shielding configurations, the algorithms streamline the design process and provide crucial support during the conceptual design phase. This breakthrough holds the promise of revolutionizing the approach to nuclear reactor design, making it more efficient and effective.

Validation through Rigorous Numerical Experiments

To ensure the reliability of their findings, the research team conducted two distinct experiments focusing on optimization simulation. The first experiment involved a straightforward 3D shielding structure, where the RP-NSGA algorithm showed significant improvements. The results were impressive, with average volume and weight reductions to just 24.5% and 14.5% of those achieved using traditional methods. The RP-MOABC algorithm delivered even more remarkable enhancements, achieving average volume and weight values of only 17.3% and 9.77%, respectively.

The second experiment tackled a more complex multi-layer, multi-material shielding design. Here, the algorithm succeeded in optimizing the structure to achieve a substantial 19.12% reduction in volume and a 24.50% reduction in weight. These experiments underscore the potential of the developed algorithms to be applied across a wide range of engineering challenges, where multi-objective optimization is crucial.

Potential Applications and Future Prospects

The implications of this research extend far beyond the realm of nuclear reactors. The algorithms' ability to handle multiple objectives and variable parameters makes them suitable for a variety of engineering fields. This adaptability is particularly valuable in industries where optimizing for multiple outcomes is essential. The success of these algorithms in nuclear reactor design suggests they could revolutionize other sectors requiring sophisticated optimization strategies.

Moreover, the integration of these algorithms into the design process of new reactor types offers a glimpse into the future of nuclear energy. As reactors become more versatile and need to meet a broader range of demands, the need for adaptable and efficient design solutions will only grow. The NEAL team's work represents a crucial step toward meeting these challenges and ensuring the safe and sustainable development of nuclear technology.

EnergyMaterials

Radiation Shielding and Metal Matrix Composites

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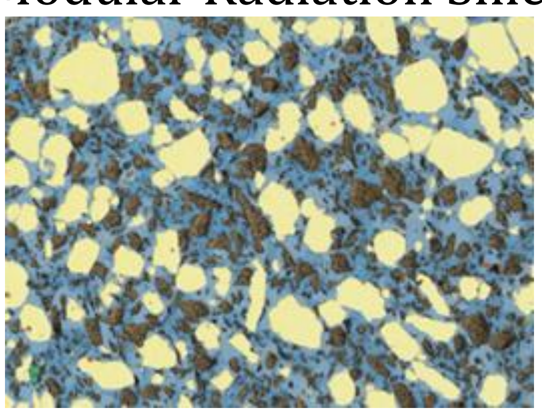
Nuclear energy is critical to curtailing climate change and achieving a carbon-neutral future. Advanced nuclear reactor concepts are rapidly progressing through design stages, and their testing, fabrication, and deployment are becoming more realistic by the day. Small Modular Reactors (SMRs) and Microreactors have been designed to reduce the cost and manufacturing burdens associated with traditional Generation II and III reactors. Microreactors are a discrete departure from typical designs, intended to be rapidly deployed to remote locations such as rural communities, mining sites, military installations, and disaster relief zones, delivering safe, clean, and reliable energy. Because they are designed to be portable, agile and rapid microreactor deployment is reliant on driving down the mass of reactor support systems, such as radiation shielding, while still providing optimal performance.

Traditional Materials Used in Radiation Shielding

Gamma and Neutron radiation must be moderated to ensure safe reactor operation. Gamma rays are easily absorbed by high-atomic number particles such as lead, or very large volumes of less dense materials such as water, steel, or concrete. Neutrons are absorbed through interactions with lower atomic number materials such as boron, carbon, or hydrogen.

For large-scale reactors, massive volumes of water and concrete knock down radiation levels, but SMRs and mobile microreactors require more elegant solutions. Designing radiation shielding materials that can combine gamma and neutron attenuating constituents has the potential to drive down overall system mass and simplify designs. By advancing radiation shielding to be more compact and lower density, project weight budgets can be redirected to allow for efficient reactor construction, deployment, and operation.

CPS' Modular Radiation Shielding



CPS is developing advanced composite radiation shielding to support microreactor transport and operations. By combining high-density gamma shielding constituents and low-density neutron absorbers in an aluminum matrix with our QuickSet™ Injection Molding system, CPS is able to create customizable radiation shielding composites for both gamma and neutron shielding in a single envelope. The aluminum matrix serves to provide significant lightweighting, while still having up to 60% volume of radiation blocking elements. QIM is compatible with any metal (stainless steels, Inconel, tungsten, and others) or ceramic (silicon carbide, boron carbide, alumina, and others). By creating multimaterial preforms and infiltrating them with aluminum, CPS creates a fully dense MMC.

Two examples of CPS' radiation shielding MMCs and their performance when exposed to gamma radiation (a Co^{60} source) are shown below. The composites utilize blends of tungsten and boron carbide to simultaneously provide neutron and gamma shielding. The Half-Value-Layer (HVL) represents the thickness of material required to halve the intensity gamma radiation. HVL values for the MMC components are similar to those of steel, lead, and tungsten, but because CPS MMCs have much lower density than these materials, yield a much lighter solution.

Given an equal cross-sectional area, the "Half-Value-Mass" of each material can be calculated. In this case, assuming a 1 cm^2 area, MMC solutions are 50-60% lighter than other materials.

Material	*Co^{60} HVL (mm)*	*Density (g/cc)*	*Half-Value Mass (g)*
Concrete	60.5	2.5	15.125
Steel	21.6	8	17.28
Lead	12.5	11.34	14.175
Tungsten	7.9	19.3	15.247
Uranium	6.9	19.05	13.1445
Al-W-B4C MMC1	**15**	**4.1**	**6.15**
Al-W-B4C MMC2	**9**	**6.7**	**6.03**

By decreasing mass, CPS ensures microreactors can be transported wherever they are needed most without sacrificing the safety of the people around them. CPS continues to actively research improvements to these materials, including further lightweighting, engineered neutron and gamma attenuation properties, and development of large-scale manufacturing.