VERSATILE TEST REACTOR: CORE SYSTEM DESIGN REQUIREMENTS TO SUPPORT ADVANCED REACTOR DEVELOPMENT

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Abstract

The Versatile Test Reactor (VTR) is a reactor under development in the United States of America to provide a very high-flux fast neutron source. This reactor will accelerate the testing of advanced nuclear fuels, core materials, and other potentially irradiated components. As this reactor design effort is underway to support eventual construction and operation, a necessary step is the development of design requirements and objectives for all components and systems of the VTR. Such requirements are created in all engineering projects to ensure the delivered product can perform its' mission safely, integrate the various design teams working on interfacing systems, and provide a basis for successful project execution. Many of the VTR nuclear core requirements are typical for reactors, for example, inherently safe feedback behavior is required as a part of the design, various fuel material performance limits shall be met during certain scenarios, and the occupational and public dose limits must be below site and regulatory limits. However, some requirements are unique to VTR due to the reactor being a test reactor that can support the needs of experimenters. For example, the reactor shall be designed to allow the use of any non-control/safety rod assembly position in the core as an un-instrumented experiment position. The reactor also must be able to accommodate multiple different materials and/or fuels undergoing irradiations experiment campaigns at a time. The paper will present and discuss these reactor core system design requirements with the goal of disseminating these requirements to potential experimenters as early as possible. The work reported herein is the result of studies supporting a VTR conceptual design for DOE-NE to make a decision on procurement and, as such, is preliminary.

1. INTRODUCTION

The United States of America has determined that a need exists for a versatile, reactor-based, fast-neutron source to exist as a national user facility. The US Department of Energy (USDOE) is currently pursuing construction and operation of such a fast neutron source. The specific mission of this facility is to enable accelerated testing of fuel and materials of advanced reactor designs of interest to the United States [1]. This reactor-based fast neutron source is called the Versatile Test Reactor (VTR) and is required to begin operation by 2026.

The VTR design has progressed beyond the conceptual design stage. The associated concept is a sodium-cooled, pool-type fast reactor rated at 300 MW(th). The reactor plant associated with the reactor core would be based on the GE Hitachi Power Reactor Innovative Small Module (PRISM) design [2]. Unlike the PRISM design, however, the 300 MW(th) energy will be dissipated instead of converted to electricity. This strategy is taken so the VTR can be used solely as a neutron test source that is unencumbered by the operational implications of power generation.

A conceptual VTR reactor vessel diagram and core layout are shown in Fig. 1 and Fig. 2, respectively. The reactor is a pool-type reactor with all the liquid sodium primary coolant contained within the reactor vessel. The reactor coolant inlet and outlet temperatures are expected to be at 350 and 500°C, respectively, at a pressure slightly above atmospheric pressure. The fuelled-region of the core is 0.8 meters tall and the total reactor vessel is 17.1 meters tall. The hexagonal assembly flat-to-flat distance is 11.7 cm. The storage of 110 assemblies will be provided by either the spent fuel storage racks or the outer shield assembly positions shown in Fig. 2. These storage locations are within the reactor vessel and preclude the need to supply an external storage tank [3].

The Fig. 2 core layout shows a typical fast reactor layout with a hexagonal arrangement of driver (fuel), reflector, shield, control, and safety assemblies. The VTR includes six instrumented test assemblies and, notionally, four non-instrumented test assemblies. The specific number and position of each assembly type except the control, safety, and instrumented test assembly positions can vary according to the needs of the set of experiments to perform and reactor physics and safety constraints for a given cycle.

The driver assemblies are a hexagonal array of HT-9 stainless-steel clad rods containing uranium-plutonium-zirconium alloy fuel pins. Each assembly type contains an assembly duct to provide structural support and direct coolant flow. Reactor control and shielding is provided by B_4C pins whereas reflection is provided by HT-9 stainless-steel. The test assemblies will be discussed later.

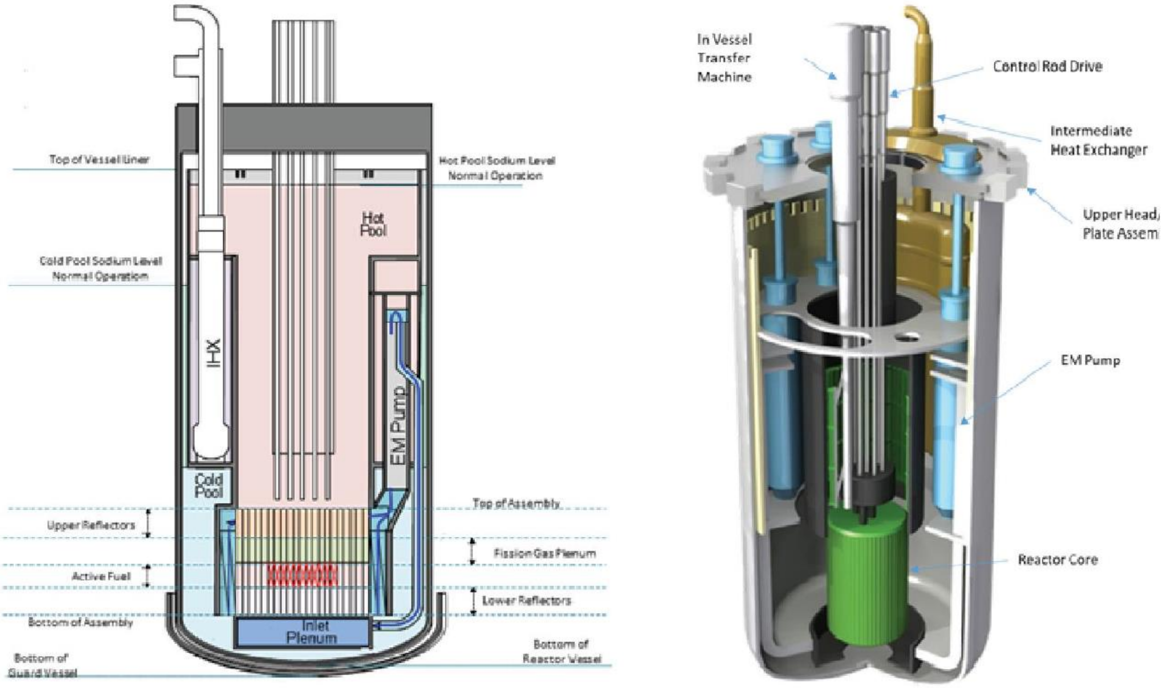

FIG. 1. Conceptual Reactor Vessel Cutaway Diagram (adapted from [3])

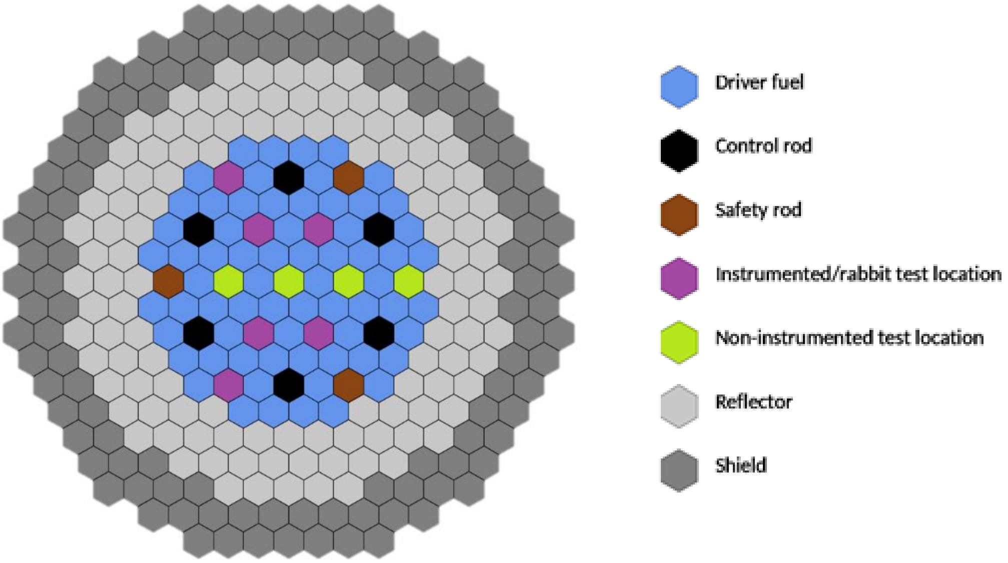

FIG. 2. Conceptual Reactor Layout

The VTR project has developed a set of requirements that are necessary to ensure the reactor can perform its' mission safely, while providing a means for integration of the various design teams working on interfacing systems, and providing a basis for successful project execution. Many of these requirements are typical of any nuclear reactor design project. For example, inherently safe feedback behaviour is required as a part of the design, various fuel material performance limits shall be met during certain scenarios, and the occupational and public dose limits must be below site and regulatory limits. However, some requirements are unique to VTR due to the reactor being a test reactor that shall support the needs of experimenters. This paper will present and discuss these requirements with the goal of disseminating these requirements to potential experimenters as early as possible.

The work reported herein is the result of studies supporting a VTR conceptual design for the USDOE to make a decision on procurement and is preliminary.

2. REACTOR CORE SYSTEM DESIGN REQUIREMENTS

While all large reactor projects have many detailed requirements, this paper will limit the discussion to those requirements of interest to those interested in performing future irradiation testing with neutrons supplied by the VTR. Specifically, this section will discuss the design requirements on the neutron flux, neutron damage rate, cycle length, test volume and irradiation length, and the types of experimental assemblies available.

Each of these are discussed in the following sub-sections. The first, Section 2.1, will describe the requirements that relate to the reactor core and plant design. The second, Section 2.2, describes the requirements related to the testing capabilities themselves.

2.1. Reactor parameters

In this section the requirements related to the attributes of the general reactor core and plant design are discussed. These are discussed first in terms of overall reactor and site safety (Sec 2.1.1) and in terms of reactor capabilities relevant to experimenters (Sec 2.1.2).

2.1.1. Reactor Operations and Safety

Many VTR nuclear core requirements are typical for a nuclear reactor. For example, requirements are present on the fuel assembly and core structural design to maintain nuclear material accountability and avoid unintended perturbations to the core reactivity and peak temperatures. Specifically, the VTR fuel assemblies and structural components are required to have design features that prevent misloading of assemblies, fuel assemblies are required to contain features to prevent misidentification of assemblies, and both the structural components and assemblies are designed so they can be consistently oriented correctly.

The VTR reactor design also has requirements that ex-core fresh and spent fuel assemblies and their casks/containers be evaluated under applicable normal and hypothetical accident conditions to ensure that safe manufacturing, transportation, and handling is possible.

The reactor core also has requirements related to maintaining the primary barrier to fission product release, including requirements to ensure effective heat transfer is available to limit the peak temperature of the cladding, maintain cladding integrity, and avoid formation of a fuel-cladding eutectic. Further, the reactor core shall be designed to ensure that inherently-safe reactivity feedback is present to preclude excessive permanent cladding strain during protected transients.

Finally, occupational and public dose limits exist as specified by applicable site and regulatory requirements. These are imposed during all aspects of reactor operation, including fuel handling, expected at-power operations, and during accident scenarios. These requirements result in a reactor design that has sufficient pool depth, a floor thickness with mitigated radiation streaming paths, radial shield assemblies to minimize the neutron flux in the sodium tank to minimize activations, etc.

2.1.2. Reactor Capabilities

As stated earlier, the mission of the VTR is to enable accelerated testing of fuel and materials of advanced reactor designs of interest to the United States. This accelerated testing is achieved through high neutron flux levels, large testing volumes, and several irradiation locations.

The VTR Project requires that the reactor provides a fast neutron flux at least 4×10^{15} neutrons/cm^2-second. In this case a fast neutron is defined as neutrons with an energy greater than 0.1 MeV. This large fast neutron flux provides experimenters with a reduced time to achieve desired neutron irradiation or burnup levels. The energy spectrum of this test neutron source is consistent with a prototypic fast reactor neutron energy spectrum. The flux requirement does not explicitly define the volume for which the high flux is present, however, given that the VTR is a fast reactor, the flux gradient will generally be weakly varying in space. A minimum photon flux is not specifically established as a design requirement as the photon flux is (generally) proportional to the neutron flux levels and is more difficult to optimize.

Consistent with the high neutron flux is a high neutron damage rate for structural materials testing. The Project specifically requires that the reactor system be capable of providing greater than 30 displacements per atom per year of operation (dpa/year) based on an HT-9 irradiation. This requirement is strongly related to the high flux requirement, however an additional requirement for the damage rate is used for additional assurance that non-fuel-bearing tests can also achieve high throughputs in the VTR. In addition to the flux levels, this dpa/year requirement is also strongly related to the next requirement, the operational tempo.

The requirements described above are not useful if the reactor is only infrequently operational. To design in robustness and flexibility of the core, refuelling apparatus, fuel storage rack locations and access patterns, et cetera, the VTR Project requires the facility and reactor are designed to meet a periodic operational schedule of 100-days of full-power operations followed by a 20-day refuelling and maintenance outage. While versatility is being designed in, experimenters should be aware that experiments which require major core re-configurations will naturally require additional long-range planning to ensure the outage windows and the needs of other experimenters are met.

Finally, an objective of the VTR Project is to achieve near-even discharge burnup in all fuel assemblies. Maximizing resource utilization is not the VTR’s primary mission, however, there are several benefits to discharging fuel as close as possible to the maximum burnup allowed by the fuel system’s qualification. Specifically, discharging assemblies when they reach maximum burnup can reduce the number of refuelling operations, minimize the number of fresh fuel assemblies required and used fuel generated, all leading to lower costs and risk. The reduction on the number of refuelling operations specifically results in a reduced refuelling outage duration, thereby increasing the overall rate of irradiation for experimenters.

2.2. Testing capabilities

This section describes the requirements related to the specifics of the testing infrastructure, separate from the core design. The first sub-section will describe the core requirements related to testing while the second provides an overview for future experimenters of conceptual test assembly designs and associated instrumentation.

2.2.3. Testing-Related Requirements

The Project requires that the VTR provide a large testing volume for irradiation samples. This test volume should be large enough that VTR can be used for assembly-scale testing and design qualification instead of sample-scale testing. This is captured by the VTR design by requiring that each irradiation test volume within the core region provides at least 7 liters for testing of large samples and the ability to accommodate self-contained cartridge loops. Further, the irradiation length (i.e., the length scale where the flux level is significant) should be typical of fast reactor designs and at least long enough that axial effects under irradiation, such as component bowing or flexing, can be adequately tested. This specific requirement for VTR is that the irradiation length provided is between 0.6 and 1.0 meters.

As shown in Fig. 2, the conceptual design for the VTR core contains 66 driver fuel assemblies, nine safety and control rod assemblies, and six instrumented test assemblies. These instrumented assemblies will be located at fixed positions within the reactor core, driven by the constraint that the instrumentation power and communication lines, conduits, cover head penetrations, et cetera, are designed to support those positions. The VTR is also designed with a requirement that the upper and lower structural components, refuelling equipment, et cetera, are designed such that any assembly position on the core support grid can be used as an un-instrumented test position with the exception of the control and safety rod positions. The specific number of these positions used by each assembly type will naturally depend on the satisfactorily meeting conservatively determined safety basis for the reactor design envelope.

The VTR is required to accommodate at least one “rabbit” irradiation system in an instrument test assembly position for rapid insertion and removal of test specimens. This is commonly used to provide shorter irradiations within a normal VTR cycle that is needed for certain materials and other samples.

Since the mission of VTR is to offer versatile and flexible irradiation capabilities, the reactor core design and supporting safety basis is required to enable accommodating several different materials and/or fuels being irradiated concurrently. This will practically be implemented through the use of a conservative safety basis and associated performance limits as well as judicious selection and analysis of core and experimental configurations to ensure the safety basis is met by a particular configuration.

2.2.4. Test Assembly Approach

There are currently four types of major assembly types envisioned for use in the VTR: Normal Test Assemblies (NTAs), Dismountable Test Assemblies (DTAs), Extended Length Test Assemblies (ELTAs), and Rabbit Test Assemblies (RTAs).

NTAs and DTAs are non-instrumented or passively-instrumented assemblies of the same size as the driver fuel assemblies. These assemblies can contain fuels or non-fuel materials for testing. These NTAs/DTAs will be outwardly similar to driver, reflector, or shield assemblies and thus will utilize the same fuel handling approach, et cetera, as standard VTR components.

ELTAs are the instrumented assemblies and, as implied by their name, are taller than standard assemblies as they extend through the reactor head for instrumentation leads, etc. A conceptual ELTA is shown in Fig. 3. ELTAs can bear fuel or non-fuel materials and can be configured as standard assemblies with instrumentation, or as cartridge loops.

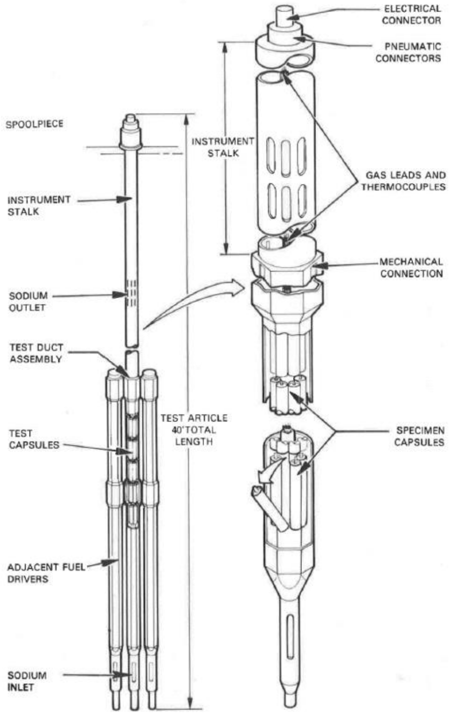

FIG. 3. Conceptual ELTA Schematic (adapted from [3])

Cartridge loops are specific assemblies which trade irradiation volume for the ability to test in coolants that are not VTR’s primary coolant loop sodium, such as sodium at differing thermodynamic conditions, molten salt, molten lead, or helium. This approach further increases the versatility of VTR by more directly supporting fuel and non-fuel material qualification efforts for many advanced reactor types. An example and preliminary cartridge loop schematic is shown in Fig. 4. In this example, the cartridge assembly effectively provides an isolated pool environment within the VTR's larger sodium pool environment with heat transfer, generation and removal provided as needed by the cartridge design. As can be seen, cartridge assemblies provide a reduced irradiation volume for a given test.

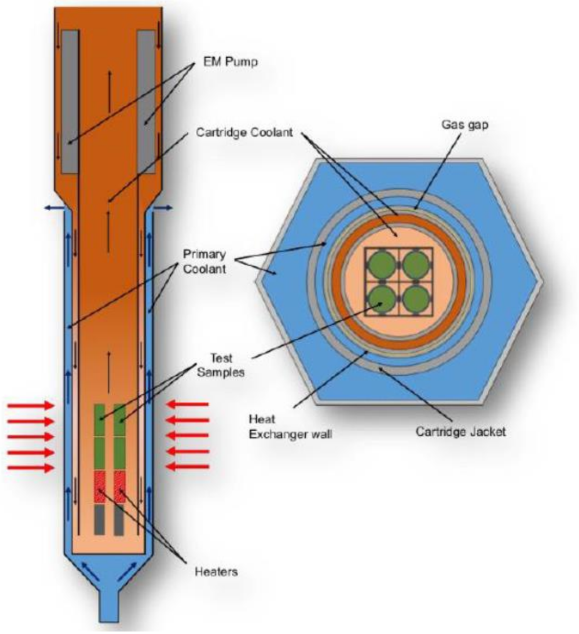

FIG. 4. Example Cartridge Assembly (adapted from [3])

The RTA is a system under design that notionally consists of an experiment-bearing capsule that is propelled through the rabbit tube for irradiation and later recovery. This is typical of most rabbit-like systems used in test reactors. Due to the volume necessary for the system components of the RTA, it is unlikely that the RTA can accommodate experiments of large samples. Further, it is also likely that the sample would need to be weakly absorbing to avoid rapid and local power disturbances in the reactor.

3. CONCLUSION

The VTR is under development by the USDOE to provide a high-flux irradiation capability for advanced reactors. This paper describes nuclear reactor core system requirements of the VTR that are specifically relevant to potential users of the facility. Specifically, this paper describes the requirements relating to: the peak flux (greater than $4x10^{15}$ neutrons/cm^2-sec), the neutron damage rate (30 dpa/year), the operational tempo (100 days at power, 20 day refuelling outages), the testing volume (7 L per position) and length (0.6 to 1.0 meters), and finally the testing versatility (6 instrumented test positions including 1 potential rabbit, and placement of non-instrumented tests in any location not taken by a control or safety rod) being designed in to the reactor. The work reported herein is the result of studies supporting a VTR conceptual design for the USDOE to make a decision on procurement and is preliminary.

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