INTRODUCTION

The development of more efficient, reliable, and cost-effective nuclear technologies has been accomplished by testing and evaluating the performance of fissile and non-fissile materials under neutron rich environments. In addition, irradiation tests have been done to support the validation and verification of systems and components of nuclear reactors for licensing purposes. Currently, there is a lack of access to fast neutron sources for civilian research. Access to fast neutron technologies has been fulfilled by using foreign nuclear research reactors, but many research institutions do not have access to this technology. Therefore, efforts are ongoing to develop the Versatile Test Reactor (VTR). This sodium-cooled fast test reactor has the primary purpose to perform irradiation tests on fuels and materials to understand and evaluate their performance. It is envisioned that the capabilities of the VTR shall be expanded even further to produce isotopes of interest, perform reactor system component tests, and provide the infrastructure needed to test and evaluate the maturity of new nuclear technologies.

The following paper presents the test vehicles that are under consideration for their addition to the VTR design. The first section provides a brief explanation of the proposed experimental capabilities that are envisioned for this future irradiation test facility. The second section provides a summary of test vehicles that are anticipated for their inclusion. The test vehicles analyzed in this paper were designed to be used in the Experimental Breeder Reactor II (EBR-II), the Fast Flux Test Facility (FFTF), the BOR-60 and the Multipurpose Fast Neutron Research Reactor (MBIR). The envisioned experimental needs of the VTR consists of the inclusion of various test assemblies and test loops that provide access to high quality neutron fluxes for instrument verification along with the provisions for tests to be conducted in isolation from the primary coolant, real time monitoring of systems, dynamic control of experiment operating conditions, as well as on-line sample extraction and storage systems for post-irradiation examination.

I. VERSATILE TEST REACTOR

The VTR is a fast flux test reactor designed to perform irradiations on nuclear fuels, materials, and components. Even though its mission is focused on irradiation tests on prototypical fuels and materials, it is anticipated that this experimental facility will have a multi-purpose mission for its expected operational lifetime. The main requirements and preliminary assumptions for the reactor include [1]:

- Achieve fast flux of approximately $4 \times 10^{15} \text{n/cm}^2\text{-sec}$, with prototypical spectrum
- Maximize dpa/year to >30 dpa/year
- Reach a thermal power of 300 MW
- Effective testing height ≤ 1 m
- Provide flexibility for novel experimental techniques
- Being capable of running loops representative of typical fast reactors (potential coolants: Sodium, Lead, Lead Bismuth Eutectic, Helium and Molten Salt)
- Being capable of performing large number of experiments simultaneously.

The areas that the VTR will be able to support are presented in the following sections.

I.A. MATERIALS AND FUEL TESTING

Irradiation testing consists of the exposure of fuels and materials to neutrons in a controlled environment. These tests are vital for the collection of information regarding the performance of the sample under a preset environment. The data is obtained using three different approaches: 1) sample behavior analysis using macroscopic observation, 2) post-irradiation examination, and 3) fuel and coolant temperature, coolant flow rate, neutron flux, and volume pressure measurements collected from the test vehicle or from the reactor during irradiation. These irradiation tests can be accomplished using several methods including capsule tests, rapid extraction tests ‘rabbit’, open-core testing, closed loop testing, and whole-core testing.

I.B. ISOPOTE PRODUCTION

The production of isotopes is important due to the fact that several cancer treatments and medical imaging are performed using radioisotopes. These isotopes can be produced using accelerators, nuclear reactors, or cyclotrons. Since isotope production systems around the world are being decommissioned, the VTR offers its potential application for the production of isotopes of interest.
I.C. REACTOR SYSTEM COMPONENT TESTING

The VTR can be used for the commercialization of sodium, lead, gas and molten salt technologies since its infrastructure offers a unique opportunity to test components such as control systems, heat exchanges, pumps, valves, seals, and other in-core components.

II. TEST VEHICLES

In support of the future nuclear experimental needs, several test vehicles are being considered for their integration to the VTR design. It is considerably important to develop an appropriate infrastructure that will provide access to a wide range of testing capabilities. Therefore, several test vehicle designs from other fast reactors may be used to inform and streamline the design. The exploration of multiple concepts promotes the use of the most efficient design, and consequently bolster the ability to perform multiple experimental tests. The experimental capabilities of the VTR can be increased by placing multiple test vehicles at different locations in the core as seen in Fig. 1. The 10 green sections in the VTR core map are the possible positions for the cartridge closed loops, open-core instrumented sub-assemblies, and the rabbit facilities. Some of the driver fuel assemblies (see Fig. 1) will be replaced by open-core un-instrumented sub-assemblies.

II.A. OPEN-CORE SUB-ASSEMBLIES

Open-core sub-assemblies are experimental devices that are designed to fit within the reactor core and have direct contact with the primary coolant. The internals of these sub-assemblies are modified to house experimental samples and change the local thermal-hydraulic boundary conditions of the sub-assembly. Open-core sub-assemblies can be classified as instrumented and un-instrumented.

Instrumented sub-assembly is attractive to users since it can be equipped with measuring instrumentation, such as flowmeters, thermocouples, flux monitors and fission gas pressure transducers, that provides online measurements. However, this test device can be positioned in a limited number of positions within the core since the reactor vessel head needs to be penetrated in order to allow the instrumentation leads to be connected from the sub-assembly to the terminal box for the instrument leads.

The absence of instrument leads in the un-instrumented sub-assembly allows it to be placed at any location within the reactor core. This test vehicle is favored over the instrumented sub-assembly since the execution is relatively quick and inexpensive. Several open-core sub-assembly designs from other reactors have been evaluated, but special attention has been given to the Materials Open Test Assembly (MOTA) and the Fuels Open Test Assembly (FOTA) used in the FFTF. In addition, the designs of the In-Core Instrument Test (INCOT), Instrumented Subassembly Test (INSAT) used in the EBR-II, and the Instrumented In-Pile Experimental device envisioned for the MBIR are being...
studied in order to design instrumented and non-instrumented sub-assemblies for the VTR. Due to the versatility that the open-core sub-assemblies provide, it is estimated that 15 un-instrumented sub-assemblies shall replace some of the driver fuel assemblies, and 6 or 7 of the 10 test positions shown in Fig. 1 shall be occupied by instrumented sub-assemblies.

II.B. EX-CORE DEVICES

Ex-core devices are located just outside of the reflector to avoid perturbations to the driver core, and provide access to reduced neutron fluxes. The three access types that are contemplated for inclusion are:

1. Line-of-sight thimbles: Penetrate the vessel cover at a slight angle and terminate at the core mid plane. The end point of the thimble can be located inside or outside of the reactor vessel neutron shield.
2. Curved ‘j’-tubes: It is similar to the line-of-sight thimble, but the neutron shielding needed is considerably reduced.
3. Dry well: The dry well consists of a large penetration in the vessel head that allows a cylindrical dry tube to be inserted into the reactor cooling pool. This access port allows the irradiation of large objects that cannot fit in the other thimbles.

In addition to the three access ports mentioned above, it is envisioned that 3 neutron beam ports will be included into the VTR design. The technology of the 2 beam ports used in the EBR-II will be used to inform and streamline the design of the VTR beam ports. The EBR-II had two neutron beam ports, J-2 and O-1 thimbles, whose temperatures were controlled by flowing air through them. The J-1 thimble is smaller than the O-1. The O-1 thimble was able to provide access to lower flux than the J-2 thimble since its end point was fastened to the outside of the reactor vessel [2]. Fig. 2 shows a schematic of the beam ports used in the EBR-II. Some of the properties of these two thimbles are shown in Table I.

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TABLE I. O-1 and J-2 Thimble Properties [3]

<table>
<thead>
<tr>
<th>Port</th>
<th>Neutron Flux ([\text{n/cm}^2\text{s}])</th>
<th>Gamma Flux ([\text{R/hr]})</th>
<th>Temperature of Operation ([\text{°F}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>O-1</td>
<td>(6.4\times10^8)</td>
<td>(5.5\times10^7)</td>
<td>100 - 695</td>
</tr>
<tr>
<td>J-2</td>
<td>(8.0\times10^7)</td>
<td>(1.2\times10^7)</td>
<td>459 - 858</td>
</tr>
</tbody>
</table>

The inclusion of three neutron beam ports to the VTR design will allow the user to perform irradiation tests on reduced neutron fluxes, and control the temperature of the test sample, as needed.
TABLE II. External Closed Loop vs. Cartridge Loop

<table>
<thead>
<tr>
<th>Parameters</th>
<th>External Closed Loop</th>
<th>Cartridge loop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Large due to the presence of intermediate loop. Will need to be placed in the reactor</td>
<td>Somewhat small as it fits mostly within the reactor vessel, with its instrument head protruding out at the top of the vessel</td>
</tr>
<tr>
<td>Design</td>
<td>Simple as most of the heat transfer mechanisms are located outside the test device</td>
<td>Challenging design as the space for the pumps, control valves, heat exchangers, coolant chemistry measuring devices and other instruments is limited</td>
</tr>
<tr>
<td>Coolant mass flow rate</td>
<td>Can be adapted as needed</td>
<td>Can be manipulated as needed, but likely lower than external loop</td>
</tr>
<tr>
<td>Flow direction</td>
<td>Up or down as needed</td>
<td>For optimal heat exchange, exterior flow must go downwards, and the flow past fuel must go up</td>
</tr>
<tr>
<td>Heat transfer</td>
<td>Can dissipate a large amount of heat towards the primary coolant</td>
<td>Heat transfer is limited to the length of the heat exchanger and the internal pump, to provide enough flow rate</td>
</tr>
<tr>
<td>Radiation protection</td>
<td>Required and challenging since it exits reactor vessel</td>
<td>No need since cartridge loop will be located in within the reactor</td>
</tr>
<tr>
<td>Transient testing</td>
<td>Several transient testing capabilities available</td>
<td>Limited transient testing since heat removal and flow rates are constrained</td>
</tr>
<tr>
<td>Cost</td>
<td>Expensive due to inclusion of intermediate and external loops</td>
<td>Comparatively cheaper</td>
</tr>
</tbody>
</table>

An example of a self-contained loop that was successfully implemented was the Independent Lead Channel (ILC) used in the Russian reactor, BOR-60. The ILC had lead as its internal coolant which was flown through the assembly using centrifugal pumps driven by a magnetic clutch using an external motor. The loop housed four fuel pins in order to conduct fuel irradiation in a lead flowing system, under fast neutron spectrum. [3] The ILC also contained electric heaters in order to make sure that the lead coolant did not solidify. Self-contained sodium loops were also considered for installation in the BOR-60 reactor, but never fabricated and deployed. In addition to the closed loop used in the BOR-60, the MBIR external loop channel exhibit promising futures that can help to develop an efficient closed loop for the VTR. It is envisioned that up to 2 closed loops shall be used in the VTR.

III. CONCLUSION

The lack of access to fast neutron sources has restrained the ability to perform research on fuels, materials, and reactor system components within the U.S. The VTR will be designed to fulfill current and future domestic needs of fast neutron sources by providing a wide range of testing capabilities. The inclusion of several test vehicles will enable the user to have access to high quality neutron fluxes for instrument verification along with the provisions for tests to be conducted in isolation from the primary coolant. Also, some of the test vehicles will allow real time monitoring of irradiation test experiments, dynamic control of experiment operating conditions, as well as on-line sample extraction and storage systems for post-irradiation examination.

It is anticipated that the VTR will be able to perform irradiation tests using instrumented and un-instrumented open-core sub-assemblies, closed loops with special emphasis on cartridge loops, rabbit systems, neutron beam ports, line-of-sight thimbles, curved ‘j’-tubes, and large ‘dry wells’. The inclusion of these test vehicles into the VTR design shall provide the user with the testing capabilities to support the evolution of advanced nuclear fuels and materials technology across the full spectrum of technology readiness levels over the years of its operational lifetime.

REFERENCES