# The NuScale Micro-reactor Design – Innovation for 21st Century University Research and Training Needs

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NuScale Power has designed a passive micro-scale nuclear reactor suitable for a variety of applications, from a high temperature research reactor to micro-grid power production to industrial heat supply. The design of the NuScale Micro-reactor (MRX) is still in development, allowing it to be customized for its application. The use of a high conductivity metallic moderator-coolant allows for flexible arrangements of fuel tubes to create flux traps to locally increase neutron flux for accelerated irradiation. Reactivity control is accomplished by the chemical absorption and desorption of hydrogen from the moderator-coolant, precluding reactivity insertion transients and costs associated with control rods or moving reflector drums. The high temperature moderator-coolant facilitates a liquid uranium alloy fuel capable of operating with enrichments between 4.95 and 19.5 weight percent $U^{235}$ depending on the use case. An online continuous fission product removal system reduces xenon transient impacts, reduces the core source term, and increases core lifetime.

## 1. Introduction

The NuScale MRX system includes a variable enrichment thermal fission nuclear reactor design that utilizes uranium-iron (UFe) liquid fuel and metal alloy calcium-hydride calcium (MACH-C) heat transfer fluid and moderator. This combination of fuel and coolant facilitates low pressure, high temperature heat transfer and a simplified means for reactivity control. High temperature heat enables the use of thermophotovoltaic (TPV) cells for direct power conversion to DC electricity or high temperature Brayton cycle turbines for high power conversion efficiency. TPV power conversion uses no moving parts resulting in simplicity, ease of scale-up, and improved reliability compared to thermo-mechanical power conversion systems (e.g., Brayton and Rankine cycles). Fig. 1 illustrates the NuScale MRX conceptual design and major components.

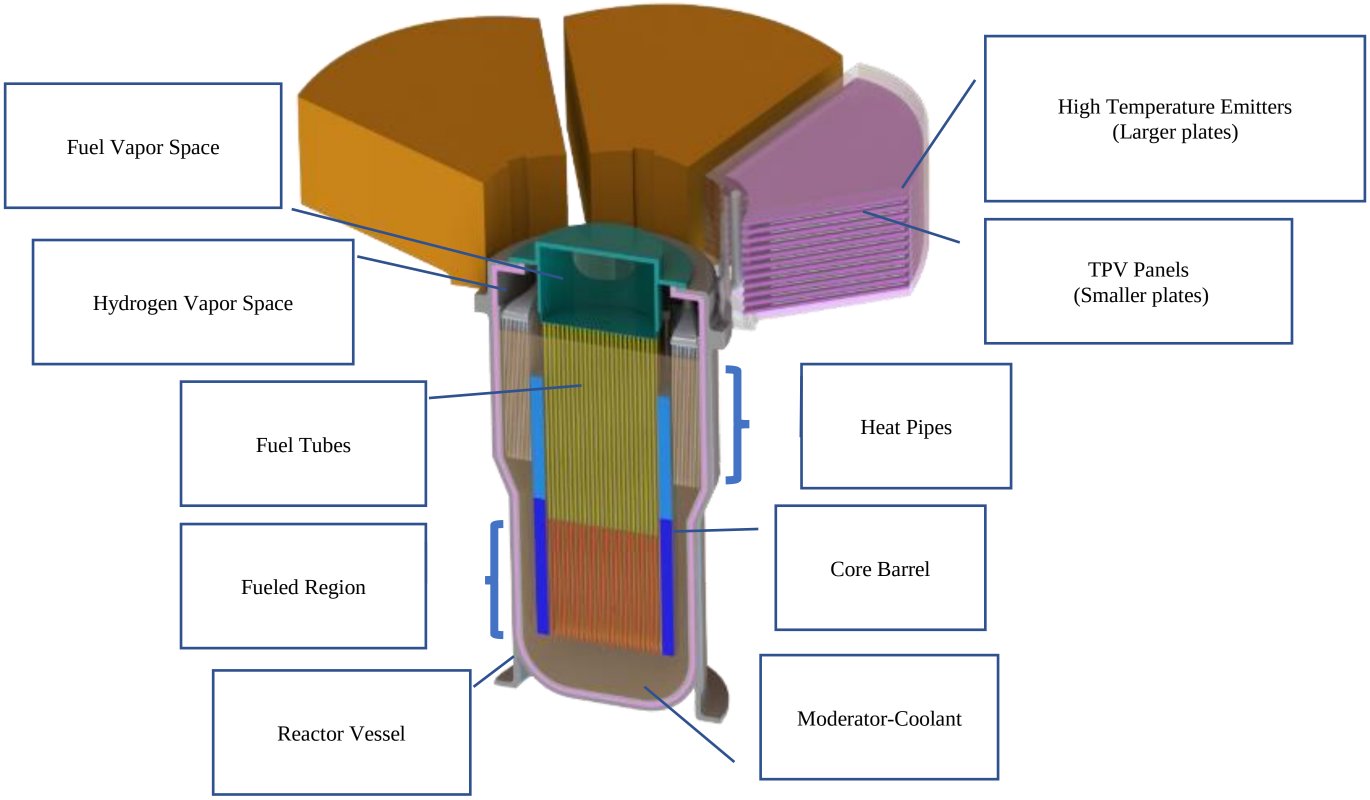
## 2. Design Elements

There are three innovative design elements in the NuScale MRX: the fuel, the moderator-coolant, and the power conversion system. The ultimate heat rejection and shielding, while designed to fit the NuScale MRX, are similar to components utilized in other reactor designs. The functional outcomes of the novel design elements are:

1. Fully passive primary cooling loops;
2. Fully passive secondary cooling loops; and
3. No mechanical reactivity control mechanisms such as control rods, control drums, or movable reflectors.

The NuScale MRX is based on a safety-by-design methodology. In the event of potential component failures or system malfunctions, the reactor power is limited through inherent passive design features to maintain fission product retention and heat removal functions. This capability eliminates the need for a safety-related reactor control system/reactor protection system and the need for constant licensed operator monitoring. Additionally, power is not required to safely shutdown or indefinitely maintain the safety of the reactor.

**Fig 1**. Cross section of NuScale MRX with major components labeled



## 2.1. Fuel

The NuScale MRX utilizes a liquid fuel alloy composed of uranium and iron. A range of iron concentrations can be used to allow the melting point of the mixture to be as low as 800°C, with the phase diagram described in Ref [1]. Decreasing the concentration of iron increases the melting point, but allows for a smaller fuel mass to be used by increasing the relative uranium concentration. To reduce proliferation concerns, the maximum enrichment used is 19.5 weight percent U-235, categorized as HALEU, but enrichments as low as 4.95 weight percent can be used. The fuel is comprised of an array of fuel tubes all independently containing their liquid fuel volume. There is an in-tube neutron reflector positioned above the fuel level to improve the neutron economy. The fuel tubes share a gas volume above the reflectors that allows volatile and noble fission product gases to mix from all fuel tubes.

### 2.1.1. In-tube Fuel Circulation

The circulation of the fuel within the tube offers several advantages over a more traditional solid fuel with a helium gap.

- It allows for much better heat transfer and a lower temperature gradient from the fuel centerline to the bulk coolant temperature by both removing the standard gas gap and by facilitating convective heat transfer currents within the fuel.
- The distribution of the fuel by the convective currents homogenizes the fuel, eliminating axially dependent burnup and allowing for more complete use of the fissile isotopes.
- The fissile isotopes are not the only contents to circulate; the fission product entrained within the fuel will circulate and both volatile and noble gas components will have the opportunity to escape into the vapor above the fuel. This is discussed further in Section 2.1.2.

However, there are challenges from the direct contact between the fuel and the fuel tube, such as:

- Chemical interactions between the fuel and fuel tube. This is being addressed by careful selection of the fuel tube material to maximize its resistance to chemical attack by the fuel.

### 2.1.2 Fission Product Removal System

The fission gas volume above the fuel is cooled to condense and absorb volatile fission products from the gas through a filtering mechanism in the fission product removal system (FPRS). Condensable fission products, such as cesium and iodine, will be cooled and collected in appropriate media within a filtration system. Noble fission product gases like xenon and krypton can be separated and stored separately. The removal of Xe-135 and its precursor I-135 reduces the magnitude of startup reactivity transients and allows for a longer operating life for the reactor. There is some evidence to suggest that the operating temperatures are high enough that samarium will become volatile, even further reducing fission product poisoning by removing Sm-149.

### 2.1.3 Reflectors

An aluminum oxide reflector has been selected for use in the MRX. Its light weight, efficient scattering, and historic role as a reflecting material make it an ideal candidate. There are two separate reflector volumes within the system:

- Axially within the fuel tubes, directly above the fuel level
- Radially within the core barrel structure separating the coolant-moderator riser flow path from the downcomer flow path

## 2.2 Moderator-Coolant

The reactor moderator-coolant is liquid MACH-C, which functions as both heat transfer fluid and neutron moderator for the reactor. The NuScale MRX is designed such that natural circulation is sufficient to cool the reactor under all modes of operation, requiring no pumps to circulate the moderator-coolant. The hydrogen component of MACH-C serves as the neutron moderator and is used to control core reactivity. The hydrogen content of the

MACH-C is adjusted by adding or removing hydrogen to a separate dedicated vapor space in contact with the MACH-C liquid surface. Varying hydrogen neutron moderation through the reversible thermochemical reaction of hydrogen with liquid calcium dispersed in liquid metal provides a simple and reliable means for reactivity control. The globalized change in moderation, as opposed to the use of localized control rods for power control, can help prevent nonhomogeneous spatial power distribution that can occur with control rod insertion and removal.

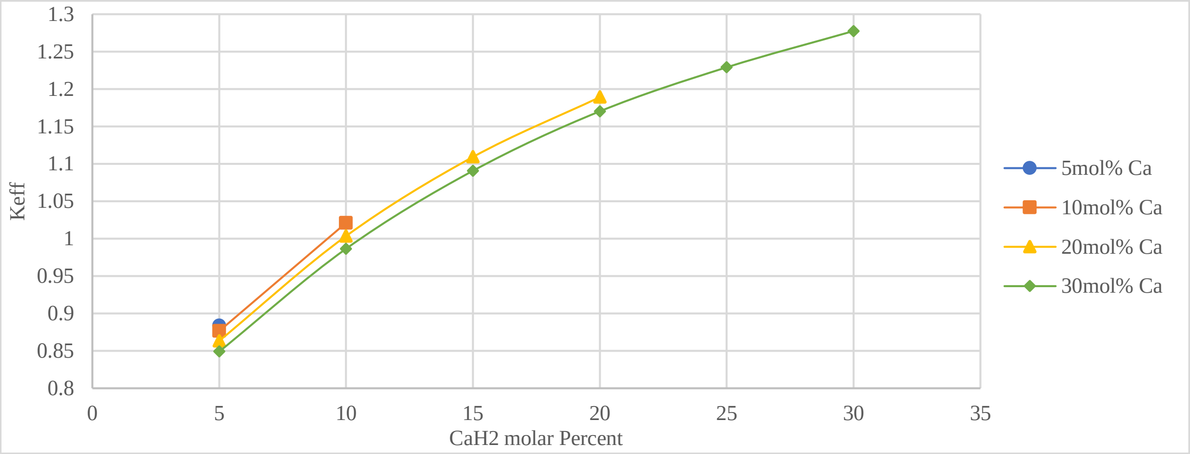
Liquid MACH-C offers two mechanisms for negative reactivity control through temperature effects:

- The density of the MACH-C is reduced at increased temperatures
- The saturation pressure of hydrogen in the MACH-C increases with increased temperature. This leads to a decrease in the concentration of hydrogen in the MACH-C because more hydrogen is contained in the vapor space at higher temperatures.

Both of these mechanisms reduce the hydrogen density, which in turn reduce moderation and core power output.

Fig. 2 shows the change in the system effective neutron multiplier ($k_{eff}$) as a function of calcium hydride concentration for varying levels of beginning of life calcium concentration. The X-axis represents the molar percent of $CaH_2$ as a function of total system concentration, while the legend represents the molar concentration of Ca at beginning of life, with no hydrogen added. This means that the 20 atom percent Ca case can have a maximum $CaH_2$ concentration of 20 atom percent, assuming the hydrogen can fully saturate the calcium. However, it is unlikely that full saturation will occur at operating temperatures and pressures. This means that despite the parasitic neutron absorption effect of calcium, higher concentrations must be used to ensure that sufficient hydrogen density for criticality and power control can be formed in the MACH-C.

**Fig 2**. Impact of calcium molar percent and calcium hydride molar percent on criticality at BOL



## 2.3 Hydrogen Control System

Hydrogen contained in the MACH-C is regulated by adding or removing hydrogen to the gas volume above the liquid MACH-C surface. Hydrogen pressure during power operation is less than 150 kPa (21.8 psia) to eliminate the need for a pressure vessel. To achieve and maintain shutdown, hydrogen is removed from the reactor until the system is subcritical. Hydrogen will need to be removed past the point of subcriticality due to the potential for a return to criticality event as the fuel increases in density while cooling. By eliminating the need for mechanical reactivity control systems (e.g., control drums and control rods) and xenon transients, the reactor design, reactor fabrication, and control system design is simplified to improve overall MRX system reliability and eliminate postulated positive reactivity insertion events.

### 2.3.1 Control

Power maneuvering is simplified by the release of xenon from the fuel as well as the negative temperature coefficient associated with liquid fuel and moderator. As a result power, can be controlled by regulating the amount of heat removed from the system. In other words, hydrogen content in the system does not have to be actively adjusted to change power. The system self-adjust to a new power level and temperature as the amount of heat removed from the system changes. Hydrogen is slowly added to the reactor over the life of the core to compensate for fuel burnup.

## 2.4 Structural Materials

Standard materials used in other nuclear reactors will not be suitable for containing the novel fuel or MACH-C. Instead, the reactor liner, fuel tubes, and heat pipes will be composed of a molybdenum alloy that can withstand the temperature, chemical composition, and radiation fields that will be present during operating conditions.

## 2.5 Heat Exchanger System

Heat pipes will be used to transfer the heat from the coolant-moderator to the power conversion system. High temperature heat delivered via heat pipes can be converted to electrical energy using either thermophotovoltaics cells or themo-mechanical power systems, discussed further in Section 2.6. Regardless of the power conversion system, the heat exchanger within the vessel will be composed of an array of heat pipes arranged vertically into the moderator-coolant.

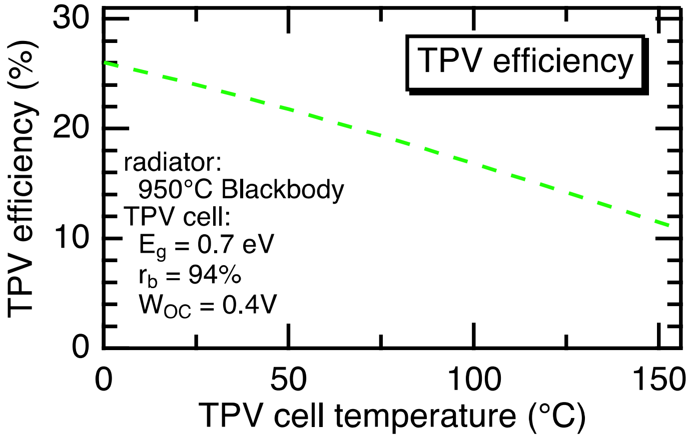
The heat pipe arrangement yields substantial benefits to their operating capability. In addition to the capillary pumping power provided by the internal structure of the heat pipes, the vertical positioning of the evaporator region below the condenser region gives a boost to the maximum power throughput of the heat pipes by allowing gravity to pull the condensed working fluid back to the evaporator region.

## 2.6 Power Conversion

For a TPV power conversion system, the high temperature heat pipes transfer heat from the MACH-C moderator onto integral flat radiator plates, which radiate heat onto TPV cells for power conversion. The TPV cells can be bandgap-engineered for optimal power output and maximum conversion efficiency. Reflectors will be incorporated to return unused sub-bandgap photons to the radiator, significantly increasing the system-level efficiency and reducing the cell-cooling requirements. Waste heat is removed from the TPV cells to maintain cells at low temperatures, suitable for efficient operation. Modeled TPV efficiency values noted below and in Fig. 3 assume a single-junction TPV cell with a 0.7-eV bandgap, 94% sub-bandgap reflectance, and bandgap-voltage offset at “1 sun” of 0.4 V. These values are readily achievable in practice. Two-junction designs could substantially improve the efficiencies.

At a radiator surface temperature of 950°C, and a TPV cell operating temperature of 50°C, the TPV panels have a conversion efficiency of approximately 22%. Increasing the radiator temperature and decreasing the TPV surface temperature can increase the efficiency of the power conversion; however, increasing the radiator temperature would increase the operating temperature for components within the reactor, and decreasing the TPV surface temperature would require increasing the power and/or water requirements for cooling.

**Fig. 3 -** Efficiency of TPV power conversion system as a function of TPV cell temperature



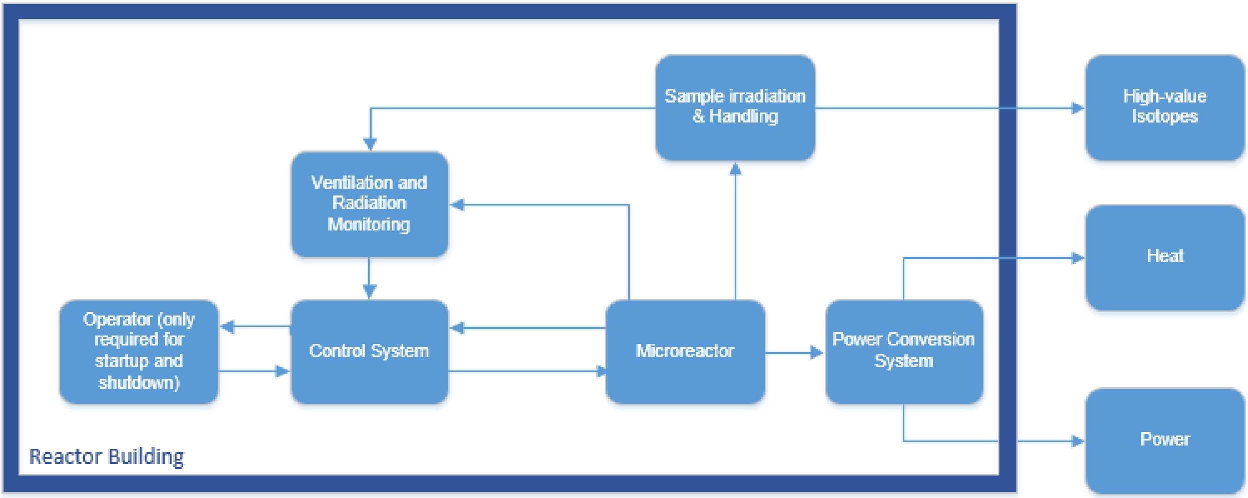
### 2.6.1 Alternative Power Conversion

A Brayton cycle gas turbine with an intermediate heat exchanger to connect to heat pipes is an alternative to the TPV power conversion system. It is a trade-off of power conversion efficiency and high technology readiness level for high reliability and low maintenance. The other benefit of a Brayton cycle (simple cycle) is the high waste heat rejection temperature, which can be over 450°C. This exhaust can be used as the heat source for district heating, hydrogen generation, or to connect to a Rankine steam turbine to extract more power. This power conversion option allows for the use of standard commercially available turbines. However, a non-standard intermediate heat exchanger will be fabricated.

### 2.6.2 Co-Gen Opportunities for Campuses

The proposed use for the NuScale MRX on university campuses is presented in Fig. 4. Ideally, the system would be providing power, heat and irradiation facility access to fast and thermal neutrons for research, training, and commercial applications.

**Fig. 4 -** Microreactor Systems of Interest



## 2.7 Building Infrastructure

The MRX is compact, contained entirely within its own reactor building as shown in Fig 5. Fig 6 illustrates scale with a human silhouette for reference. The reactor bay provides access to irradiation facilities and a separate area outside of the reactor area or building for power conversion and district heating. The thermal/power output connects to existing campus district heating infrastructure and also to the grid. Additional lab space would be provided for control panels, offices, material handling areas, and general storage.

Power conversion equipment for a Brayton cycle system includes: compressor, intermediate heat exchanger, turbine, and exhaust to recuperator before combustion process and/or district heating. For a TPV system, the equipment includes voltage regulators, coolant pumps, and interfaces for ultimate heat rejection outside the building.

**Fig 5** - Top-down view of NuScale MRX and facility.

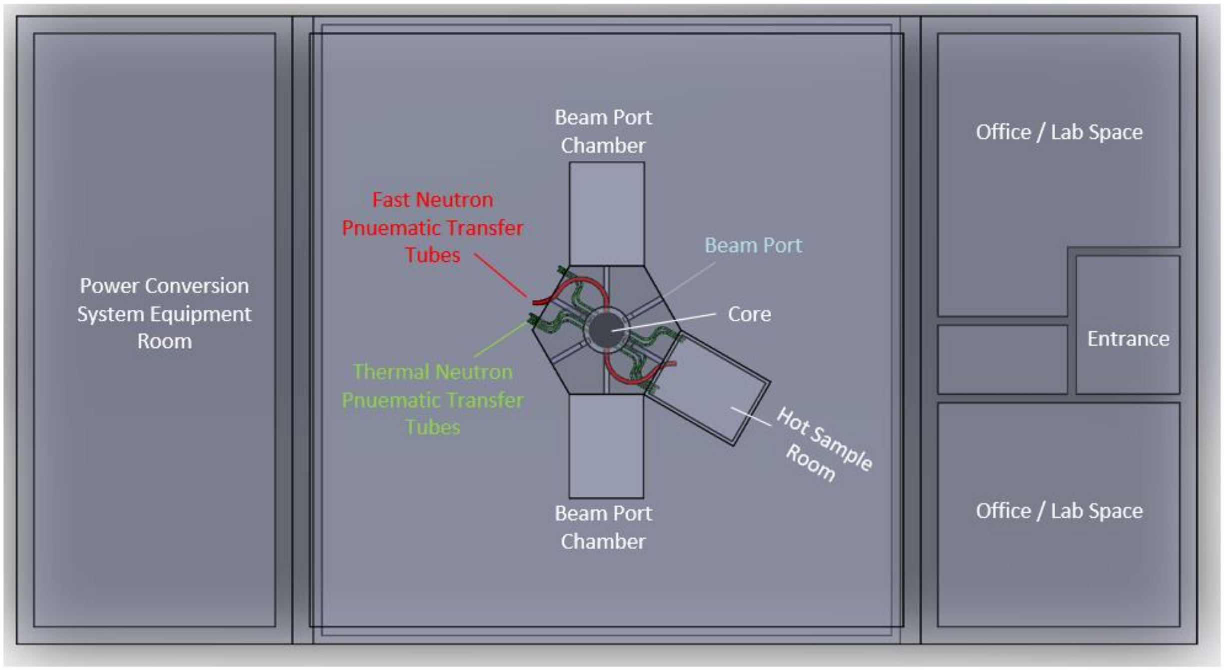
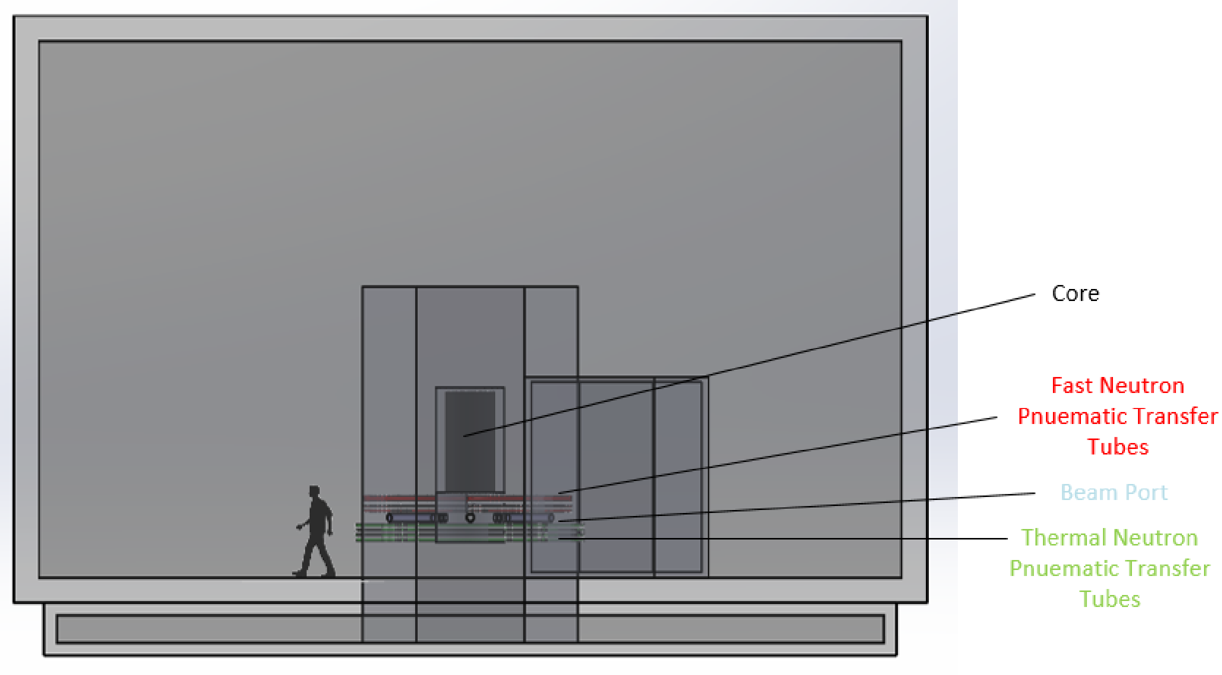


**Fig 6** – Side view of MRX with pneumatic transfer tubes and beam ports labeled



### 2.7.1 In-Core Irradiation Facilities

There are locations for multiple pneumatic transfer systems, also called rabbits, for fast and thermal neutron irradiation of samples. The rabbit design is a push through with separate sample in and out areas to minimize contamination spread. The design minimizes the amount of neutrons and other products leaving the reactor shielding through rabbit inlet and outlets. A poison may also be added to the inlet and outlet of the rabbit to further reduce radiation leakage. There could be 5 to 6 irradiation locations in the fast neutron flux at the core center, and up to 20 irradiation locations in a thermal neutron area below the core. Standard rabbit sample tube size is approximately 1 inch diameter and 4.5 inches long, and there may be capability up to 4 inch diameter samples. Gases other than standard air may be used as the pneumatic transfer medium due to the temperatures and material compatibilities of the vessel.

### 2.7.2 Beam Ports

There are multiple (possibly up to 6) beam ports to support experiments and activities, such as neutron scattering, prompt-gamma analysis, neutron physics, neutron transmutation doping (NTD), neutron radiography, neutron depth profiling, positron imaging, and neutron activation analysis. The beam port configuration allows flexibility for future use and the ability to be reconfigured after the facility and reactor construction is complete.

## 3 Safety Case

The design of the NuScale MRX is intended to be passively safe, with certain traditional accidents mitigated or eliminated by design. The lack of large diameter penetrations below the liquid level of the moderator-coolant eliminates large-break loss of coolant accidents (LOCAs), and minor leaks in the vessel will be easily detectable and self-sealing due to the high melting point of the moderator-coolant. Failures in heat pipes and even entire heat pipe cartridges will not result in unsafe conditions due to the distributed cooling system.

Safe shutdown conditions in the MRX are maintained by reducing the hydrogen content within the vessel to the point that criticality is no longer maintained.

## 3.3 Maximum Hypothetical Accidents

The modeled operating schedule of the NuScale MRX assumes 10 years of continuous full power operations, and, for safety evaluations assumes a fission product inventory consistent with 10 years of operations. In the event of a complete core inventory release of all available volatile and semi-volatile fission products and moderator-coolant activation products, the dose at a site boundary 25 meters away is below dose limits in 10 CFR 20. The fission product removal system greatly reduces the available volatile inventory within the fuel, which allows for this reduced dose consequence of a release.

## References

[1] T. Chen and T. Smith and J. Gigax and D. Chen and R. Balerio and L. Shao and B. Sencer and J. Kennedy. “Intermetallic formation and interdiffusion in diffusion couples made of uranium and single crystal iron,” Journal of Nuclear Materials. 467. 82-88. 10.1016/j.jnucmat.2015.05.026.