MARVEL FUEL SYSTEM AND PROGRAM OVERVIEW

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The US Department of Energy Microreactor Program has initiated the deployment of a new microreactor at the Idaho National Laboratory (INL). INL, in collaboration with Los Alamos National Laboratory, Argonne National Laboratory, and TRIGA International, has designed the Microreactor Applications Research Validation and Evaluation (MARVEL) which aims to be a first of its kind microreactor. The MARVEL reactor design was inspired by both the System for Nuclear Auxiliary Power (SNAP) program of the 1960's and TRIGA research reactors. To be discussed will be the fuel system of MARVEL, and the concepts shared from SNAP and TRIGA, that have led to the design and qualification of the MARVEL fuel system.

1. Introduction

The Microreactor Applications Research Validation and EvaLuation (MARVEL) (Figure 1) project is producing a high temperature liquid metal-cooled nuclear test bed at the Idaho National Laboratory (INL) to ultimately improve integration of microreactors to end-user applications. Using High Assay Low Enriched Uranium (HALEU) the reactor will produce roughly 85 kW thermal energy. Using sterling engines, some of this thermal energy will be converted to electric energy [1]. Through the use of off the shelf components, and historical data from both TRIGA Research Reactors and the System for Nuclear Auxiliary Power (SNAP) program, the program aims to deploy the MARVEL reactor by late 2024/early 2025.

Figure 1. Rendition of MARVEL reactor concept [6]

This ambitious effort seeks to design, authorize, construct, test, and operate the reactor within five years. To construct and operate the MARVEL reactor in a timely manner, the system will utilize materials and component designs which have already been used, qualified, or licensed from previous reactors. The MARVEL reactor will be located at the INL Transient Reactor Test (TREAT) facility and will use the existing 304 stainless steel-clad U-ZrH fuel system developed for TRIGA research reactors by General Atomics and purchased from TRIGA International. This fuel has been previously qualified under the United States Department of Energy's Reduced Enrichment for Research and Test Reactors (RERTR) Program using a variety of different enrichments, uranium loading compositions, and fuel element geometries.

Even though the regulator of the MARVEL reactor is the United States Department of Energy, the standards and approach recommended by the Nuclear Regulatory Commission is well-defined and utilized here. Following NUREG-1537 regulatory guidance, the report by Evans *et al.* [2] documents the authorization case for the MARVEL fuel system's application to MARVEL and establishes stable and predictable fuel performance during the most thermophysically unfavorable conditions achievable in the MARVEL reactor.

2. Discussion

2.1. Fuel System

The MARVEL fuel system is composed of 36 fuel elements (Figure 2), with the primary heat transfer medium (primary coolant) being a sodium-potassium eutectic. For the purpose of this discussion, the fuel system includes, and is limited to the following—the fuel elements and its internal components, and the interaction between the cladding material and the primary coolant.

The content of the fuel element is similar to a TRIGA cluster element (Type 304 stainless steel cladding and end plugs, annular U-ZrH fuel meats, central Zr rod, Mo disk separating the bottom fuel meat and bottom graphite neutron reflector, and axial graphite reflectors) (Figure 3). However, the reactor requires an additional 10 inches of fuel in each element for neutronic reasons. The MARVEL fuel elements will contain 5 fuel meats, making the fuel stack height 25 inches (Figure 3); typical fuel stack height in a TRIGA cluster element is 15 inches. Each U-ZrH fuel meat will be composed of 30 wt% uranium, enriched to about 19.75%, contain no erbium, and with a nominal H/Zr ratio of about 1.6. The primary coolant will be a sodium-potassium eutectic (eutectic temperature of about -13ºC, composition of 21 wt% Na/79 wt% K [3]) which has adequate thermophysical properties (thermal conductivity given by equation 1 [13]) and boils above 785 ºC at 1 atm [13].

Equation 1. $\kappa \left[\frac{W}{cm\cdot{}^{\circ}C}\right] = 0.214 \pm 0.002 + (2.07 \cdot 10^{-4})t - (2.2 \cdot 10^{-7})t^2; t\ given\ in\ {}^{\circ}C$

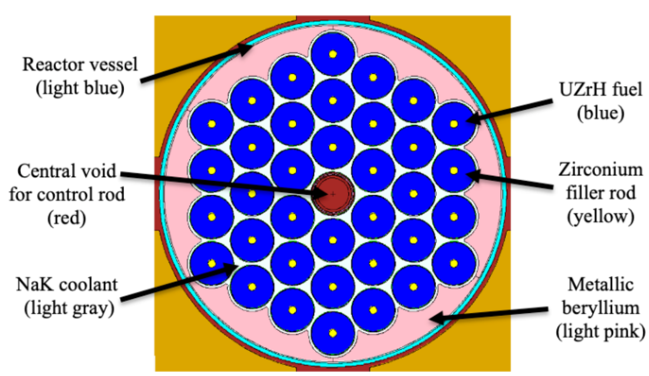

Figure 2. Radial cross section of the MARVEL core [5]

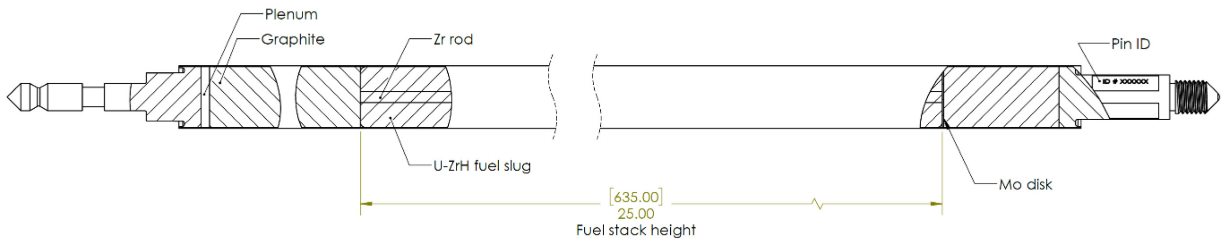

Figure 3. Schematic of MARVEL Fuel element [2]

2.2. Material interaction

Understanding the fuel-cladding and cladding-coolant interaction is crucial as the cladding is the primary pressure boundary, and containment of fuel and fission products. Keiser *et al.* have shown that for an ideal diffusion couple (minimal surface oxide, and intimate contact as a result of a 3 μm surface roughness from polishing) the interaction between as fabricated TRIGA fuel (30 wt % U, ~20% enriched) and Type 304 stainless steel is of little concern at temperatures well above the predicted peak cladding temperature for MARVEL (550 °C) [10]. Thus, of primary concern for MARVEL will be the interaction between the cladding and the primary coolant.

The SNAP-10A experiment utilized Na-K as the primary coolant [7], and while austenitic stainless steels were investigated for SNAP iterations [8, 9], the SNAP-10A program ultimately chose to use Hastelloy-N as the cladding material [7]. With this in mind, the MARVEL program has relied on historical data for the interaction between Type 304 stainless steel and eutectic Na-K [2, 4]. The interaction of concern for MARVEL is intergranular and pitting corrosion particularly as a result of high oxygen impurities in the Na-K [11]. Table 1 lists corrosion data for Type 304 stainless steel in liquid Na-K at 650 and 760 °C with <20 ppm O_2, modified from Perlow [12] and Zimmerman [11]. Evans *et al.* analyzed MARVEL fuel performance assuming a relatively high oxygen impurity of ~12 ppm [2]. For comparison, the oxygen content in the sodium coolant of the Experimental Breeder Reactor-11 (EBR-II), was measured to be less than 1 ppm [14].

Table 1. Corrosion of Type 304 stainless steel in liquid NaK-78 [11, 12]

Time [h]	Temperature 650 °C		Temperature 760 °C	
	Attack depth [μm]	Observation	Attack depth [μm]	Observation
1500	0	No observable attack	0	Slight evidence of decarburization
2500	35.5	Intergranular	35.6	pitting corrosion
3500		General corrosion	33	intergranular corrosion
4500	338.1	Pitting	58.4	decarburization

Investigation of austenitic stainless steels (series 300), corrosion in a high temperature Na-K environment was also conducted by Hoffman [4]. Samples of Types 304, 316, and 348 were exposed to Na-K at temperatures between 537 and 760 °C for up to 14,200 hours. While microstructural changes were observed, such as sigma phase precipitate formation, the operability of the cladding did not degrade due to corrosion; drastic changes to the mechanical properties were not observed. As such, it is expected that the use of Type 304 stainless steel will behave similarly in MARVEL as to what was tested by Hoffman since the cladding temperature during normal operation is estimated to be about 550 °C, and maximum coolant temperature is estimated at about 540 °C [2].

2.3. Reactor comparison: MARVEL, TRIGA, SNAP-10A

While the MARVEL concept was inspired from the designs of TRIGA Research Reactors and the SNAP-10A experiment, there are several similarities and differences that should be highlighted. Table 2 lists the critical characteristics of the three reactor concepts. MARVEL shares a number of similarities with TRIGA, namely the fuel element—U-ZrH fuel clad in Type 304 stainless steel. The similarities shared with the SNAP-10A experiment are the fuel type (U-ZrH) and the primary coolant (Na-K).

Table 2. Comparison between TRIGA, SNAP-10A, and MARVEL reactors [2]

FUEL ELEMENT COMPONENT	PARAMETER	TRIGA	SNAP-10A	MARVEL
Fuel Meat	Fuel Type	U-ZrH	U-ZrH	U-ZrH
	Fuel Pellets per Element	3 - 4	1	5
	Fuel Elements in the Assembly	60 - 100	37	36
	Uranium (wt%)	8 - 45	10	30
	Enrichment (%)	19.75 - 93	93	19.75
	H/Zr, *x*	1.0 - 1.7	1.6	1.6
	Fuel Pellet Height (mm)	118 - 127	311	127
	Fuel Pellet OD (mm)	13 - 36	30.7	34.80
	Fuel Pellet ID (mm)	0 - 7	0	6.35
	BA in Fuel Meat	Er (natural)	None [a]	None
	BA in Fuel Meat (wt%)	0 - 3	0	0
Cladding	Cladding	304 SS [b]	Hastelloy N	304 SS
	Cladding OD (mm)	13.7 - 37.6	31.75	35.92
	Cladding ID (mm)	13.2 - 37.1	30.99	34.90
	Cladding Thickness (mm)	0.51 - 0.76	0.38	0.51
	End Fittings	304 SS	Hastelloy N	304 SS
Gas Gap and Plenum	Gap and Plenum Fill Gas	Air	Helium	Air
	Gap Size (µm)	25 - 250	76	50
	Pressure (atm)	1	0.1	1
Graphite	Top Graphite Height (mm)	40 - 100	N/A	66.04
	Top Graphite Diameter (mm)	27.4 - 35.6	N/A	32.74
	Bottom Graphite Height (mm)	40 - 100	N/A	86.87
	Bottom Graphite Diameter (mm)	27.4 - 35.6	N/A	32.74
	Diffusion Barrier Disc	Mo, None	--	Mo
Operational Parameters	Max Power (Steady State) (MW_{th})	0.01 - 3	0.034	0.085
	Max Power (Pulsing) (MW_{th})	6400	N/A	N/A
	Burnup Limit ($MWd \cdot kgU^{-1}$)	200	90	2.5
	Peak Cladding Dose (dpa)	Unknown	Unknown	0.32
	Fuel Temp. Limit (K)	1223	Unknown	1150
	Coolant	Water	NaK-78	NaK-78
	Nominal Coolant Outlet Temp. (K)	< 360	817	805
	Time Exposed to Hot Coolant (Years)	N/A (water)	1.15 [c]	2

[a] The SNAP-10A cladding inner surface was coated with a Solaramic film, which was 50-100 µm thick and had an initial Sm_2O_3 BA content of 3 $mg \cdot cm^{-1}$.

[b] Most TRIGA reactors utilize 304 SS as cladding, but 304L SS, Incoloy 800, and Hastelloy-x are also licensed under NUREG-1282.

[c] Though the original SNAP-10A design was intended to operate for about 1 year, NASA predicted the SNAP-10A reactor could have operated for 5 years or more.

3. Summary

To summarize, the MARVEL program aims to deploy a first of its kind microreactor at the Idaho National Laboratory within the next 1-2 years. While this schedule is ambitious the program has leaned heavily on the already-licensed fuel concepts designed by General Atomics and TRIGA international, in addition to data collected by the SNAP-10A experiment to evaluate and qualify the fuel system.

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