

Core Component Manufacturing of Heat Pipe Reactor for Power Supply in Extreme Environments

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1. Introduction

As the value of space development increases, space nuclear reactors, featuring lightweight, high-power density, and safety, are being considered as the energy source for space missions. In extreme environments such as space, polar regions, and special regions (defense), an environmentally independent and economical energy source is required, and the heat pipe nuclear system is being considered as one of the candidates. Heat pipe reactors (HPRs) with monolithic cores are solid-state with a robust form that are advantageous for transportation conditions and extreme operating environments, and possess many positive characteristics such as long life and excellent safety. In this regard, active research is being conducted worldwide, led by NASA and the U.S. DOE. However, research into their manufacturing remains relatively limited. Research is underway to utilize metal hydrides as moderators in heat pipe reactor designs. ORNL and LANL, with the TCR program, have successfully developed manufacturing technologies using direct gaseous hydriding and powder metallurgy. However, the ease of fabrication into components and the performance are still not sufficient. In the case of Westinghouse's eVinci, which is the most advanced in terms of commercialization plans, graphite is used as the moderator instead of metal hydride because it is easier to manufacture and has extensive data available. In the research, various fabrication methods were examined and process development was conducted to produce core components for Korean HPRs including metal hydride moderator, cladding and shield.

2. Core Component manufacturing of HPRs

2.1 Conceptual core design of the Korean HPRs [1]

The Korea Atomic Energy Research Institute (KAERI) initiated the development of key technologies for a space reactor with the following design requirements in 2019.

1. Life time > 10 years
2. Operating temperature: 700°C to 750°C
3. Thermal power: 5 kW(thermal)
4. ²³⁵U enrichment < 20.0 wt%
5. Mass < 1200 kg, height < 5 m, diameter < 2 m
6. Shielding design to protect the reactor system

As shown in **Fig. 1**, the epithermal reactor employs annular-type UO₂ fuel rods with an yttrium hydride (YH_{1.8}) moderator rod positioned centrally to enhance moderation efficiency. MLI (multilayer insulation) to wrap around the moderator monolith to prevent core heat loss. The reflector is installed outside the MLI. The radiation shielding was used 90 wt% enriched lithium hydride (LiH) and stainless steel 316 casing.

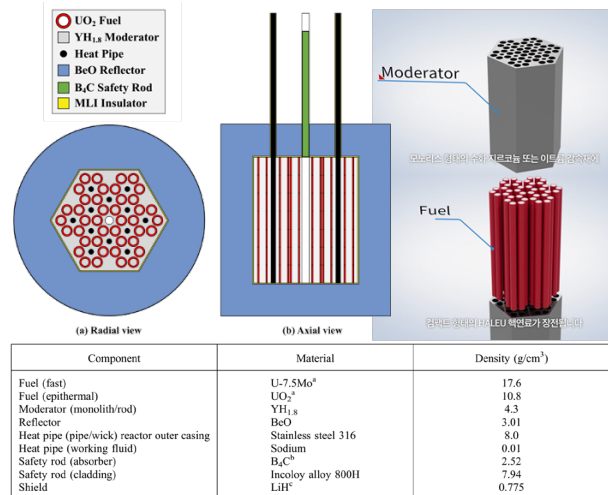


Fig. 1. Conceptual core design of the Korean space heat pipe reactor (epithermal, 5 kW_{th}) [1].

2.2 Metal Hydride Moderator (ZrHx, YHx)

Metal hydride (ZrH_x, YH_x) was chosen as a moderator for HPRs, which requires high hydrogen inventory, low neutron absorption cross-section, and high stability, as shown in **Fig. 2**. The preferred method for manufacturing hydrides is to manufacture them through gaseous hydriding of bulk metals, but there are various other methods for manufacturing them through powders (**Fig. 3**). They can minimize texture formation possibly leading to uneven dimensional changes due to irradiation growth and thermal expansion. As shown in **Fig. 4**, all possible methods were utilized and successfully adopted, but some methods had their drawbacks. When using metal powder, a gaseous hydriding process must be undergone after bulk manufacturing, which can cause cracking or dimensional changes. In powder metallurgy, additional

machining is required to achieve the desired complex component shape.

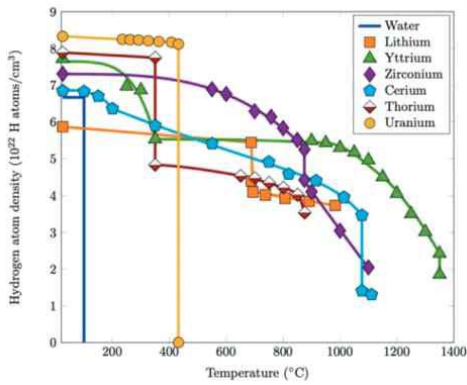


Fig. 2. Hydrogen retention of different metal hydrides compared to water at 1 atm [2].

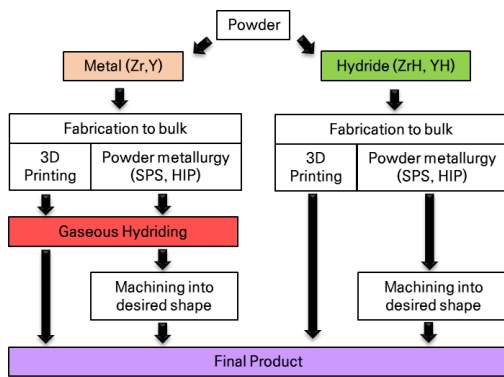


Fig. 3. Manufacturing process of metal hydride components using powder [3]

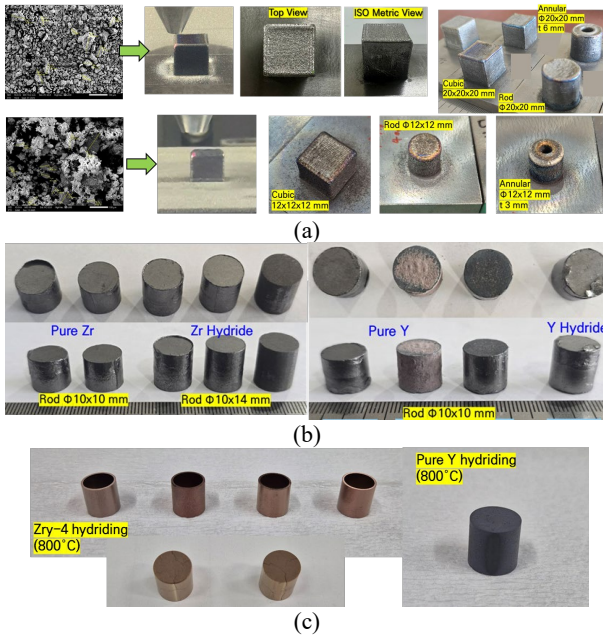


Fig. 4. Hydride fabrication by various methods (a) additive manufacturing, (b) powder metallurgy (spark plasma sintering) and (c) direct gaseous hydriding [3]

The advanced manufacturing (AM) technologies, such as spark plasma sintering (SPS) and direct energy deposition (DED), have been successfully applied in the production of hydrides. Additional research is being conducted to optimize the manufacturing process and establish a database of material properties. In addition, production at a larger scale, suitable for actual component sizes, is also planned.

2.3 Cladding

Because fuel and moderator are not made of metal to prevent cracking due to thermal gradients and stress, a metal cladding with the ability to maintain geometry and withstand stress and deformation caused by thermal gradients, thermal expansion, and creep is necessary. Also, it is used as a material for heat pipe connections. In this study, FeCrAl alloy, which has excellent creep characteristics and high-temperature properties, is proposed as a cladding material. Additionally, hydrogen permeation barrier coating is required to prevent hydrogen loss from the moderator in high temperature. The preliminary fabrication has been completed through additive manufacturing and commercial welding, as shown in Fig. 5.

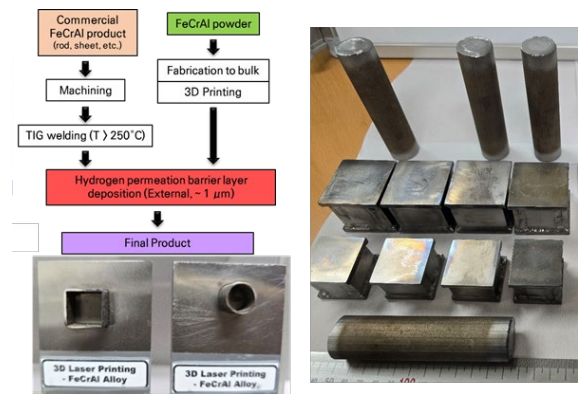


Fig. 5. FeCrAl cladding fabrication process using additive manufacturing and welding

2.4 Shield

LiH was selected as a shielding material in various USA and Soviet Union space nuclear programs, such as GE-ANP, SNAP, SP-100 and TOPAZ-I due to superior characteristics including high hydrogen concentration, excellent shielding performance, ultra-lightweight (0.775 g/ml). It was successfully manufactured by cold pressing and casting [4]. The irradiation swelling characteristics changed significantly depending on the manufacturing method, and results showing swelling of up to approximately 25% were reported. The preliminary production has been completed through cold isostatic pressing (CIP), as shown in Fig. 6.

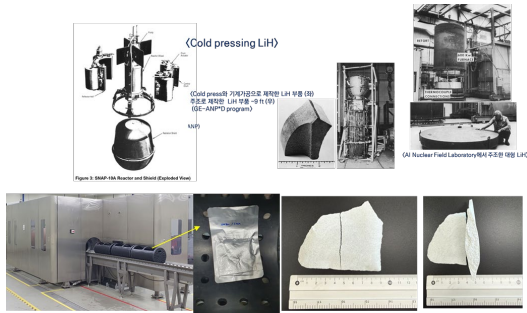


Fig. 6. LiH shield for space nuclear system [4] and preliminary fabrication using CIP

3. Conclusions

To manufacture core component of Korean HPRs for power supply in extreme environments, various fabrication methods including advanced manufacturing (AM) technologies, such as SPS and DED were examined and process development was conducted. In particular, we have successfully achieved proprietary additive manufacturing using hydride powder. The development of fundamental technologies for manufacturing other core components was also completed.

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