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기술보고서

고연소도 사용후 경수로핵연료의 장기 건식 관리기술

Long-Term Dry Storage of High Burn-UpSpent Pressurized Water Reactor (PWR) Fuel in TAD (Transportation, Aging, and Disposal) Containers

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제출문

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본 보고서를 핵비확산성 핵연료주기 기술 한-미 협력증진과제와 관련하여 “고연소도 사용후 경수로핵연료의 장기 건식 관리기술”의 기술보고서로 제출합니다.

2008. 12.

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요 약 문

현재 사용후핵연료의 건식 캐스크는 저장용 또는 저장 및 수송용으로만 개발되어 있다. 장기저장 또는 처분까지도 가능하도록 기능을 확장할 수 있다면 수송, 저장, 처분용 캐니스터의 개발이 가능하다. 이를 위하여 캐니스터의 부식 저항성, 열적 안정성, 임계 안전 제어성이 향상되도록 설계되어야 한다. 본 조사 보고서는 수송, 저장, 처분용 캐니스터에 적용될 비정질 코팅의 개발에 관하여 동경대학교의 Jor Shan Choi 교수의 자문 내용을 요약한 결과이다.

SUMMARY
(영문요약문)

A TAD canister, in conjunction with specially-designed over-packs can accomplish the functions of transportation, aging, and disposal (TAD) in the management of spent nuclear fuel (SNF). Industrial dry cask systems currently available for SNF are licensed for storage-only or for dual-purpose (i.e., storage and transportation). By extending the function to include the indefinite storage and perhaps, eventual geologic disposal, the TAD canister would have to be designed to enhance, among others, corrosion resistance, thermal stability, and criticality-safety control.

Neutron-absorbing, Fe-based, structural-amorphous-metal (SAM)coatings have been developed that are more corrosion resistant than other criticality-control materials, including Al-B_4C composites, borated stainless steels,and Ni-Cr-Mo-Gd alloys. The presence of relatively high concentration of boron in these coatings not only enhances its neutron-absorption capability, but also enables these coatings to exist in the amorphous state.

Amorphous alloy powders have been successfully produced in multi-ton quantities with gas atomization, and applied to several half-scale spent fuel storage containers and criticality control plates with the high-velocity oxy-fuel (HVOF) thermal spray process. Salt fog testing and neutron radiography of these prototypes indicates that such an approach is viable for the coating of large-scale storage containers and criticality-control plates.

Exceptional corrosion resistance has been achieved with these Fe-based amorphous-metal alloys through additions of chromium, molybdenum, and tungsten. The addition of rare earth elements such as yttrium has lowered the critical cooling rate of these materials, thereby rendering them more easily processed. Since these alloys are Fe-based, any substitution of these for high-performance Ni-based alloys is expected to result in a cost savings.

Containers used for the storage of nuclear materials, and protected from

corrosion through the application of amorphous metal coatings, would have greatly enhanced servicelives, and would therefore provide greater long−term safety. The SAM materials could be used to protect welds and heat affected zones, thereby preventing exposure to corrosive environments that might cause stress corrosion cracking. The SAM coatings, when applied on the surface of other boron−bearing basket material could also enhance the basket’s corrosion resistance and help prevent the preferential leaching of the boron.

This investigative paper introduces the use of these advanced iron−based, corrosion−resistant materials for SNF transportation, aging, and disposal. The objective of this investigative project is to explore the interest that KAERI would research and develop its specific SAM coating materials for the TAD canisters to satisfy the requirements of corrosion−resistance, thermal stability, and criticality−controls for long−term dry storage of high burn−up spent PWR fuel.

목 차

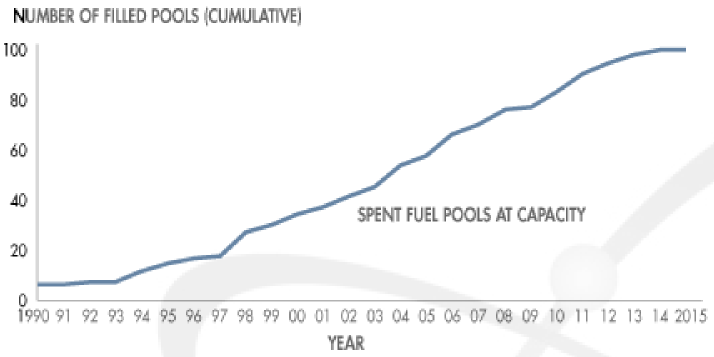
1. Spent Nuclear Fuel Arising

Global – The world´s 439 nuclear power reactors in operation today generate spent nuclear fuel (SNF) that is currently stored on-site or off-site in storage facilities. The large amount of SNF already in storage will increase, if no choices are made on spent fuel management strategies. The global cumulative amount of SNF stored is about 230,000 ton HM in 2008. It is estimated that the amount will be more than 400,000 ton HM by 2030 [IAEA 2006]. The SNF are expected to be stored for longer periods of time, awaiting final geological disposal.

Republic of Korea (Korea) – According to the revised SNF management plan announced by the Korea Atomic Energy Commission (KAEC) in September 1998, a centralized interim storage facility will be completed by 2016 [H.-S. Park, et al]. The facility will be used to store approximately 2000 ton U in its early stage and will be expanded gradually to a total scale of 20,000 ton U. As current storage capacities at reactor sites are insufficient to meet the need before the central storage facility is available, expansion of at-reactor (AR) storage capacity is being implemented at each reactor site. For PWR sites, the AR is carried out by transshipment between neighboring units and re-racking with high density storage racks using boral or borated stainless steel neutron absorbers. For CANDU site, spent fuel bundles, after 6 years of cooling are put into stainless steel baskets and transferred to the onsite concrete silo-type dry storage facility.

2. Dry Storage of SNF

Loss of Full Core Reserve – In the US, the need for alternative storage began to grow when storage pools at many nuclear reactors began to fill up with stored SNF (Figure 1). Utilities began looking at options such as dry cask storage for increasing the spent fuel storage capacity.



Note: All operating nuclear power reactors are storing used fuel under NRC license in spent fuel pools. Some operating nuclear reactors are using dry cask storage. Information is based on loss of full-core reserve in the spent fuel pools.

Source: Energy Resources International and DOE/RW-0431 – Revision 1

Figure 1 – Spent Nuclear Fuel Storage Pools Capacity in the US

SNF is currently stored in dry cask systems at a growing number of power plant sites. There are various dry storage cask system designs. Table 1 shows the NRC-approved dry SNF storage designs for general use in the US. With some designs, the steel cylinders containing the fuel are placed vertically in a concrete vault; other designs orient the cylinders horizontally (e.g., NUHOMS). The concrete vaults provide the radiation shielding. Other cask designs orient the steel cylinder vertically on a concrete pad at a dry cask storage site and use both metal and concrete outer cylinders for radiation shielding. Typical neutron absorbing materials used for the dry cask storage baskets are boral, boron-carbide composite and borated stainless steel.

Table 1 - The US Dry Spent Nuclear Fuel Storage Designs: NRC Approved for General Use

Vendor	**Storage Design Model**	**Certificate of Compliance Issue Date**
General Nuclear Systems, Inc.	CASTOR V/21	08/17/1990
NAC International, Inc.	NAC S/T	08/17/1990
NAC International, Inc.	NAC-C28 S/T	08/17/1990
Transnuclear, Inc./Areva	TN-24	11/04/1993
BNG Fuel Solutions Corp.	VSC-24	05/07/1993
Transnuclear, Inc./Areva	NUHOMS-24P NUHOMS-52B NUHOMS-61BT NUHOMS-32PT NUHOMS-24PHB NUHOMS-24PTH	01/23/1995
Holtec International	HI-STAR 100	10/04/1999
Holtec International	HI-STORM 100	06/01/2000
Transnuclear, Inc./Areva	TN-32	04/19/2000
NAC International, Inc.	NAC-UMS	11/20/2000
NAC International, Inc.	NAC-MPC	04/10/2000
BNG Fuel Solutions Corp.	Fuel Solutions	02/15/2001
Transnuclear, Inc./Areva	TN-68	05/28/2000
Transnuclear, Inc./Areva	Advanced NUHOMS-24PT1	02/05/2003

Degradation of Al-based Neutron Absorbers in Wet Storage - Boraflex^{TM} , a typical aluminum-based neutron absorber used in wet storage racks contains 46% of silica, 4% of polydimethyl siloxane polymer and 50% of boron carbide by weight. Boraflex^{TM} is susceptible to gamma radiation-induced shrinkage which potentially could cause tears and gaps in the materials. It had been observed from the Palisades spent fuel pool in August 1993 that a loss of as much as 90% of the Boraflex^{TM} was attributed to exposure to high-level of gamma radiation in conjunction with interaction with the pool water.

Another Al-based neutron absorber used in wet storage racks, boral is made out of cermets of aluminum and boron carbide particles. Boral cans were installed in the Humboldt Bay spent fuel pool in 1985-6. In November 2003, blisters were discovered on some of these boral cans.

Higher Burn-up - The higher burn-up spent fuel (>50 GWd/t) yields higher contents of transuranics (TRU). Of these TRUs, ^{238}Pu, ^{240}Pu, ^{242}Pu, ^{242}Cm, and ^{244}Cm are spontaneous neutron emitters. Their presence in the spent fuel would shift the neutron spectrum to a higher neutron energy level, and subsequently, would decrease the absorbing capability of neutron absorbers

Spent fuel assemblies discharged from PWRs in the Korea are of high burn-up (>50 GWd/t) and aged for 40 years. Long-term dry storage of these assemblies must take into account the prolonged decay heat generation, the integrity of the storage configuration for criticality controls, and the aggressive corrosion condition as the dry cask system would be exposed to coastal-moisture environment during aging storage.

3. Use of Structural-Amorphous-Metal (SAM) Coatings as Neutron Absorbers

The outstanding corrosion resistance that may be possible with amorphous metals was recognized several years ago. Compositions of several Fe-based amorphous metals were published, including several with very good corrosion resistance. Examples included: thermally sprayed coatings of Fe-10Cr-10-Mo-(C,B) [Kishitake 1996], bulk Fe-Cr-Mo-C-B [Pang 2002a], and Fe-Cr-Mo-C-B-P [Pang 2002b]. The corrosion resistance of a Fe-based amorphous alloy with yttrium, $Fe_{48}Mo_{14}Cr_{15}Y_2C_{15}B_6$, was also established [Guo 2003; Lu 2003; Ponnambalam 2004]. Yttrium was added to this alloy to lower the critical cooling rate. In addition to Fe-based materials, several Ni-based amorphous metals were developed that exhibit exceptional corrosion performance in acids [Shinimiya 2005]. Very good thermal spray coatings of Ni-based crystalline coatings were deposited with thermal spray, but appear to have less corrosion resistance than Ni-based amorphous coatings [Chidambaram 2004].

Several Fe-based amorphous alloys have been developed with very good corrosion resistance [Farmer et al. 2003-2006c; Lian et al. 2006]. Many of these alloys are based upon a common parent alloy, and can be applied as thermal spray coatings [Branagan 2000-2004]. Two of the most promising formulations are SAM1651 and SAM2X5, which include chromium (Cr), molybdenum (Mo), and tungsten (W) for enhanced corrosion resistance, boron (B) to enable glass formation and neutron absorption; and yttrium (Y) to lower the critical cooling rate.

SAM1651 – $Fe_{48}Cr_{15}Mo_{14}B_6C_{15}Y_2$
SAM2X5 – $Fe_{49.7}Cr_{17.7}Mn_{1.9}Mo_{7.4}W_{1.6}B_{15.2}C_{3.8}Si_{2.4}$

Conclusions regarding the exceptional passive film stability and corrosion resistance of this Fe-based amorphous alloy compared to crystalline reference materials were based on measurements of passive film breakdown potential and corrosion rate, as well as observed performance during salt fog testing. Such measurements enabled the corrosion performance of various Fe-based amorphous alloys, carbon steel, Fe-based stainless steels and Ni-based alloys to be directly compared.

Materials Design and Synthesis

In order to produce an amorphous metal, also referred to as a metallic glass, the high-temperature melt from which the alloy is produced must be cooled at a rate greater than its critical cooling rate (CCR). Several processes have been used to produce the materials reported here [Farmer et al. 2003-2006c].

Maximum cooling rates of one million Kelvin per second (10^6 K/s) have been achieved with melt spinning, which is an ideal process for producing amorphous metals over a very broad range of compositions. The melt-spun ribbon (MSR) samples prepared with this equipment were several meters long, several millimeters wide and approximately 150 microns thick. X-ray diffraction (XRD) data for melt spun ribbons of austenitic Type 316L stainless steel and Ni-based Alloy C-22 is compared to that of several Fe-based amorphous metals with Figures 1 through 3. The sharp peaks seen in Figure 1 are indicative of the characteristic crystalline structure of austenitic alloys, while the diffuse peaks centered at 2❑ ~ 45⊞ is characteristic of amorphous materials, which have no crystal structure.

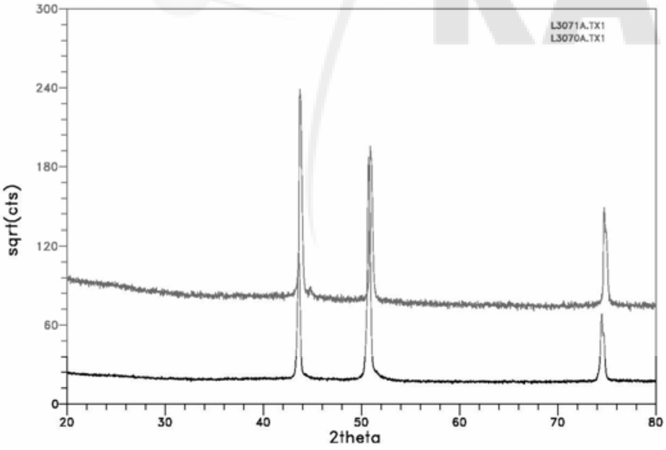


Figure 1 - X-ray diffraction data for melt-spun ribbon (MSR) samples of Type 316L stainless steel and Ni-based Alloy C-22. The strong peaks are indicative of the crystalline nature of these materials.

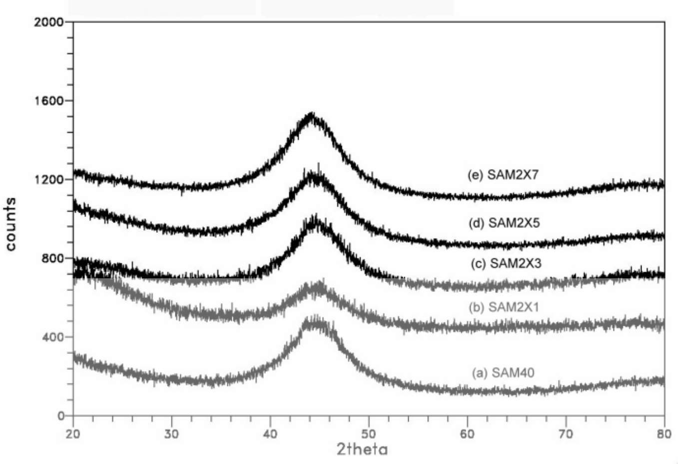


Figure 2 - X-ray diffraction data for melt-spun ribbon (MSR) samples of Fe-based amorphous metals identified as: (a) SAM40; (b) SAM2X1; (c) SAM2X3; (d) SAM2X5; and (e) SAM2X7. All ribbons were completely amorphous.

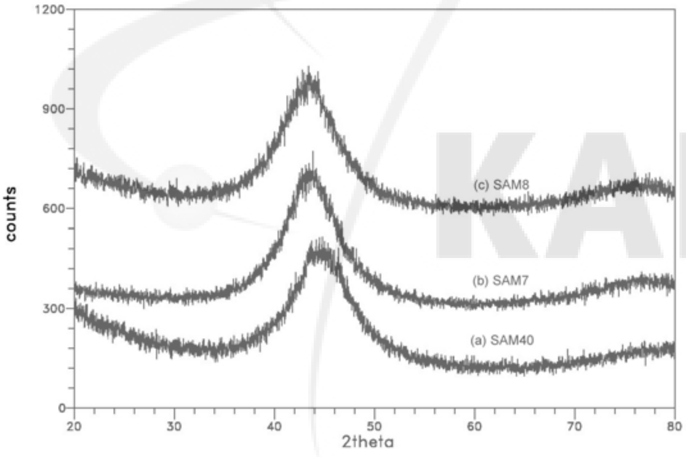


Figure 3 - X-ray diffraction data for melt-spun ribbon (MSR) samples of Fe-based amorphous metals identified as: (a) SAM40; (b) Y-containing SAM7; and (c) Y-containing SAM8. Note that SAM7 ~ SAM1651 and SAM8 ~ SAM1651 + tungsten.

Thermal spray processes require flowable powders with the proper distribution of particle sizes. Amorphous metals can be rendered as spherical particles, with a size range suitable for deposition by thermal spray processes, with gas atomization using hypersonic nozzles. The standard range of particle sizes for the high-velocity oxy fuel (HVOF) process is -53/+15 microns.

Several thermal spray processes have been developed by industry and include: flame spray, wire-arc; plasma spray; water-stabilized plasma spray; high-velocity oxy-fuel; and the detonation gun. Any of these can be used for the deposition of Fe-based amorphous metals, with varying degrees of residual porosity and crystalline structure. The coatings discussed here were made with the high-velocity oxy-fuel (HVOF) process, which involves a combustion flame, and is characterized by gas and particle velocities that are three to four times the speed of sound (mach 3 to 4). This process is ideal for depositing metal and cermet coatings, which have typical bond strengths of 5,000 to 10,000 pounds per square inch (5-10 ksi), porosities of less than one percent (< 1%) and extreme hardness. The cooling rate that can be achieved in a typical thermal spray process such as HVOF are on the order of ten thousand Kelvin per second (10^4 K/s), and are high enough to enable many alloy compositions to be deposited above their respective critical cooling rate, thereby maintaining the vitreous state. However, the range of amorphous metal compositions that can be processed with HVOF is more restricted than those that can be prepared with melt spinning, due to the differences in achievable cooling rates. While the thickness of a typical coating ranges from 0.4 to 1.0 mm (nominally 15 to 40 mils), adherent coatings with thicknesses of 7.5 mm have been produced.

Corrosion Resistance

A variety of accelerated electrochemical testing has been used to demonstrate that HVOF coatings of Fe-based amorphous metals have good passive-film stability, better than that of Type 316L and borated stainless steels, and comparable or better than that of Ni-based Alloy 22 (known commercially as Alloy C-22). The hypothesis that the corrosion resistance of Fe-based amorphous metals can be enhanced through application of heuristic principles related to the additions of chromium, molybdenum, tungsten has been found to have merit.

The breakdown and repassivation potentials for a drop-cast ingot of

SAM1651 and wrought Alloy 22 samples submersed in 5M $CaCl_2$ at 105⋕C were determined with cyclic polarization (CP), as shown in Figure 4. The thresholds for passive film breakdown on SAM1651 and SAM1651 with additions of tungsten were higher than that for Alloy 22 [Farmer 2006a-2006b]. Potentiodynamic data for SAM2X5 MSR and HVOF coating samples in seawater at 90⋕C are compared to similar data for wrought Alloy C-22 in Figures 5.

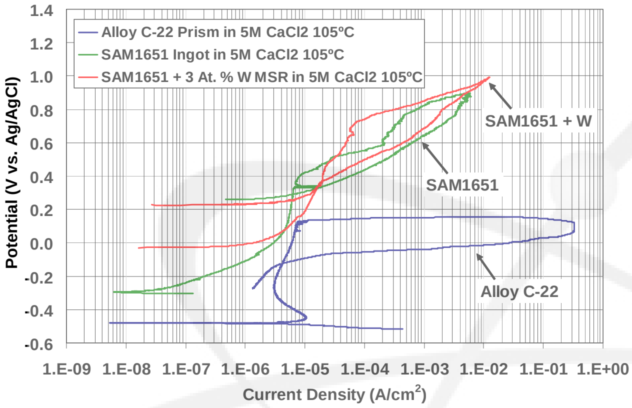


Figure 4 – CP data for Ni-based Alloy C-22, SAM1651 ingot, and W-containing variant of SAM1651, showing that amorphous metals have superior passive film stability in 5M $CaCl_2$ at 105⋕C.

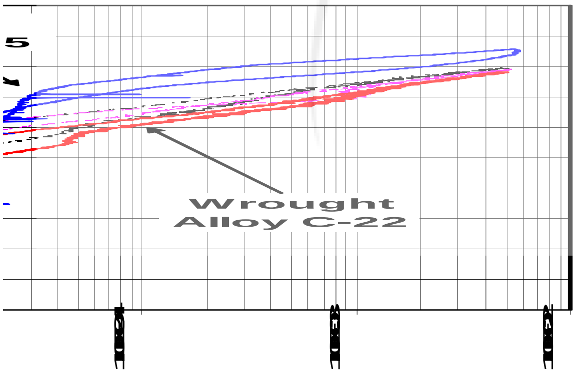


Figure 5 – CP of as-sprayed SAM2X5 HVOF coating compared to that of Ni-based Alloy C-22, demonstrating comparable or better passive film stability in seawater at 90⋕C.

Fe-based amorphous-metals, including SAM2X5 and a tungsten-containing variant of SAM1651 (SAM8), have demonstrated greater passive film stability than other well-known criticality-control materials, including neutron -absorbing Al-B_4C composites, borated stainless steels, and Ni-Cr-Mo-Gd. Supporting CP data are shown in Figures 6 and 7.

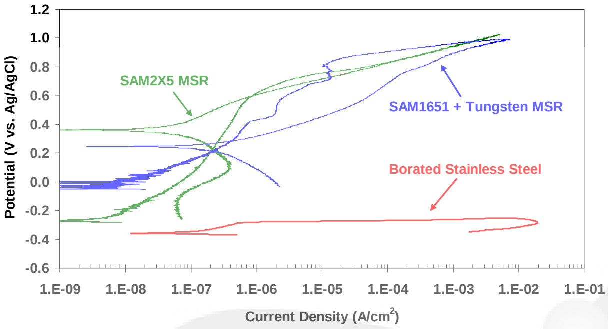


Figure 6 – CP data for SAM2X5 MSR, SAM2X5 plus tungsten MSR, and borated stainless steel in 5M $CaCl_2$ at 105#C.

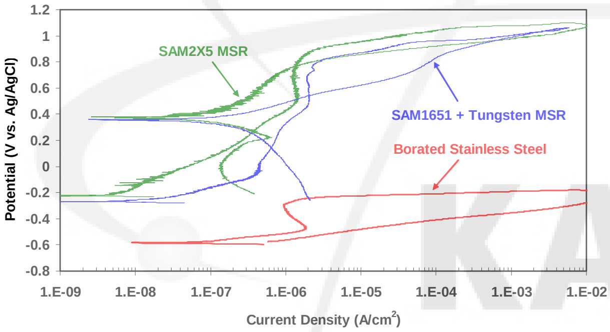


Figure 7 – CP data for SAM2X5 MSR, SAM2X5 plus tungsten MSR, and borated stainless steel in natural seawater at 90#C.

Salt fog testing was conducted on several thermal spray coatings, including HVOF coatings of Alloy 22, Type 316L stainless steel, SAM40, SAM1651, SAM2X5, and others. After 13 cycles in the GM9540P salt fog test, the HVOF coatings of Type 316L stainless steel and SAM40 showed substantial corrosion. In contrast, the SAM1651 formulation showed no corrosion after 30 cycles. The testing was continued to more than 60 cycles, with no evidence of corrosion observed. More recently, additional testing has been performed with optimized thermal spray coatings of SAM2X5 and reference samples of 1018 carbon steel, as shown in Figure 8 [Farmer et al. 2004-2006c].

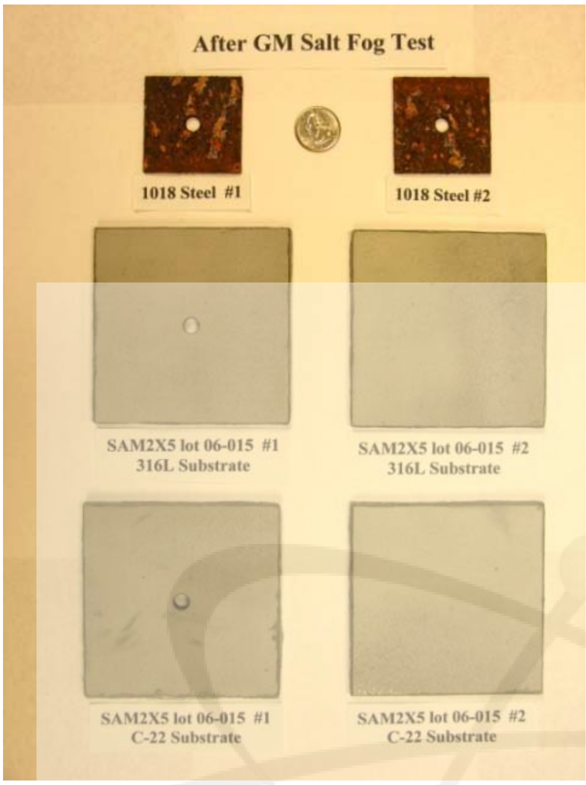
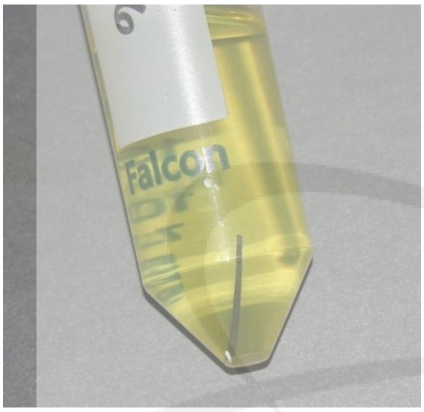


Figure 8 – Salt fog testing ot thermal spray coatings of high-boron SAM2X5 show no corrosion, where as the 1018 carbon steel reference sample shows severe attack.

Other amorphous alloys may be more corrosion resistant than the SAM1651 and SAM2X5 discussed here. In addition to synthesizing these alloys, MSR samples of $Fe_{43}Cr_{16}Mo_{16}B_5C_{10}P_{10}$ (SAM6) were also prepared [Pang 2002b]. This P-containing alloy was identified as the "Inoue Alloy" during testing. While MSR samples of Alloy 22 were completed dissolved in hydrochloric acid after several-days exposure (Figure 9a), MSR samples with SAM6 composition did not dissolve (Figure 9b). These observations are consistent with previously published electrochemical test data on this material presented [Farmer 2005; Farmer 2006a].

(a)



(b)

Figure 9 – (a) MSR of austenitic Ni-based Alloy 22 completely dissolved in concentrated HCL. (b) MSR with the P-containing SAM6 amorphous metal composition undigested in concentrated HCl.

Prototypes

The capability to scale-up the thermal spray of ultra-hard corrosion-resistant coatings of SAM1651 and SAM2X5 has been demonstrated successfully during the coating of several half-scale spent nuclear fuel containers and criticality control assemblies. The high boron content of SAM2X5 and similar amorphous alloys enable them to be more efficient neutron absorbers than conventional criticality control materials, such as borated stainless steel and Ni-Cr-Mo-Gd [Choi 2006]. The amorphous metals are also more corrosion resistant than borated stainless steel and Ni-Cr-Mo-Gd [Lian 2006].

Half-scale type 316L stainless steel criticality control assemblies (baskets) were also coated with SAM2X5. These prototypes were imaged with neutron radiography at the McClellan Nuclear Radiation Center (MNRC) 1.5 MW TRIGA reactor.

Half-scale model SNF containers made of Type 316L stainless steel were also coated with SAM2X5, which was deposited with JK2000™ gun using hydrogen fuel. These containers were fabricated from Schedule 10 pipe, had lengths of approximately 90 inches, diameters of approximately 30 inches, and wall thicknesses of approximately 0.3712 inches. The coating was nominally 17 ± 2 mils (~ 0.5 mm) thick. These half-scale containers, coated with SAM2X5, showed no corrosion after salt-fog testing (Figure 10).

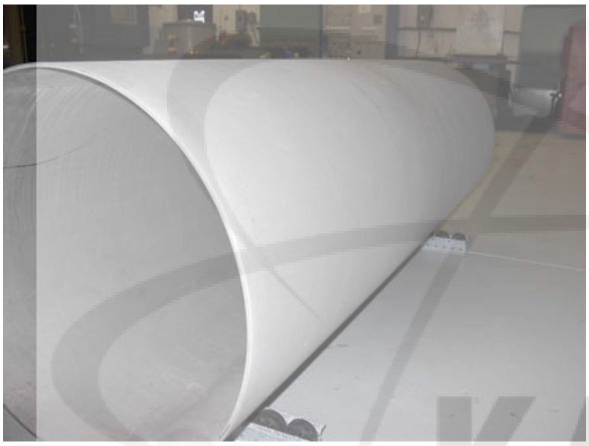


Figure 10 - Half-scale Type 316L stainless steel SNF container coated with SAM2X5 Lot # 06-015, deposited with JK2000™ gun using hydrogen fuel, photographed after atmospheric salt-fog test.

Thermal Properties

The thermal properties of these Fe-based amorphous metals have been determined [Farmer et al. 2003-2006c]. SAM2X5 had a glass transition temperature of 579°C, a crystallization temperature of 628°C, and a melting point of 1133°C. SAM2X7, an alloy in the same family as SAM2X5, but with more molybdenum, had a glass transition temperature of 573°C, a crystallization temperature of 630°C, and a melting point of 1137°C. In contrast, Y-containing SAM1651 had a glass transition temperature of 584°C, a crystallization temperature of 653°C, and a melting point of 1121°C. All values should be taken as approximate measurements, and are summarized in Table 2 for the parent alloy, SAM40, the SAM2X-series of alloys, and the Y-containing SAM1651 formulation.

Table 2 - Thermal Stability of Amorphous Metals

Alloy	T_g (°C)	T_x (°C)	T_m (°C)
SAM40	568-574	623	1110
SAM2X5	579	628	1133
SAM2X7	573	630	1137
SAM1651	584	653	1121

One of the important thermal requirements for the SNF canister is to protect the integrity of the cladding of the spent fuel elements. The peak cladding temperatures allowed in a TAD canister during different spent fuel operations are listed in Table 3. [OCRWM, 2008].

Table 3 - Peak Cladding Temperature Allowed in Spent Fuel Operations in TAD Canisters

Operation	**Peak Cladding Temperature, °C**
Spent fuel loading, including drainin drying, and backfill operations	570
Aging, storage, and transportation	400
Disposal in geologic repository	350

To ensure adequate thermal performance of the TAD canister when emplaced in the waste package for geologic disposal (i.e., the peak cladding temperature not to exceed 350 °C), the peak canister surface temperature for a TAD canister holding 21 spent PWR assemblies of burn-up of 55 GWd/t and aged for 40 years should not exceed 270 °C

In general, the corrosion resistance of such Fe-based amorphous metals is maintained at operating temperatures up to the glass transition temperature. Thus, the upper operating temperature for such materials was concluded to be T_g 🕔 579° C. This temperature is higher than the peak cladding temperature for all phases of SNF operation, including loading, draining, drying, aging, storage, transportation and geologic disposal.

Above the crystallization temperature (T_x 🕔 628° C), deleterious crystalline phases formed, and the corrosion resistance was lost. The effect of thermal aging on corrosion resistance was demonstrated with cyclic polarization testing of SAM40 (parent alloy) MSR samples in natural seawater at 90⌖C. These test showed that passive film stability was maintained after annealing at 150 and 300⌖C for 1 hour, and completely lost after annealing at 800 and 1000⌖C for 1 hour (Figure 11).

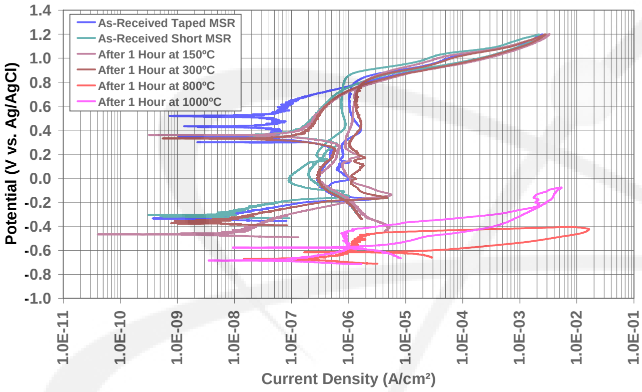


Figure 11 – CP data SAM40 (parent alloy) MSR samples in natural seawater at 90⌖C annealed at various temperatures.

Neutron Absorption Cross Section

The boron content and corrosion resistance of high-B Fe-based amorphous metals such as SAM2X5 may make them attractive candidates for criticality control applications required for the safe long-term storage of spent nuclear fuel. The average neutron absorption cross-sections of SAM2X5 and other criticality control materials, including borated stainless steel and Ni-Cr-Mo-Gd alloy, were determined in transmission at the 1.5 MW TRIGA reactor located at McClellan Nuclear Radiation Center (MNRC) [Choi et al. 2006]. Neutron absorption by HVOF coating is three-to-four times higher than that of borated stainless steel, and twice that of the nickel-gadolinium alloy, as shown in Figure 12. Data for Ni-based Alloy 22, also known commercially as Alloy C-22, and Type 316L stainless steel are given as well. The stability of these Fe-based amorphous metals after exposure to high doses of thermal and fast neutrons, which are described in Table 4, is evident from the XRD data shown in Figures 13 and 14.

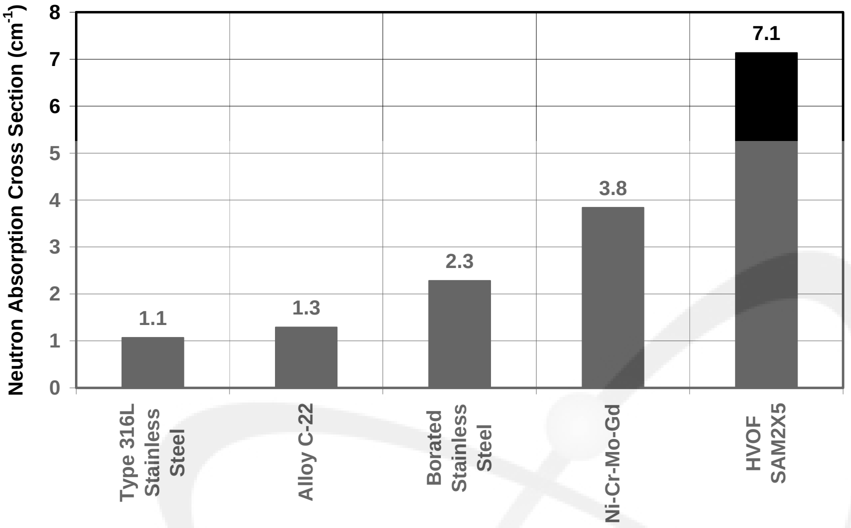


Figure 12 - Average neutron absorption cross sections of SAM2X5 compared to that of other engineering materials, including borated stainless steel and Ni-Cr-Mo-Gd alloy.

Table 4 - Neutron Exposure of Samples in Reactor

Irradiation ÷ Fast Flux = 1.6 ´ 10^{10} (n cm^{-2} sec^{-1})	**1st**	**2nd**	**3rd**
Total Time Exposure in Reactor (min)	**44**	**132**	**263**
Total Exposure Fluence (flux ´ time)	**4.3´10^{13}**	**1.3´10^{14}**	**2.6´10^{14}**
Equivalent Geologic Repository Time (years)	**670**	**~2000**	**~ 4000**

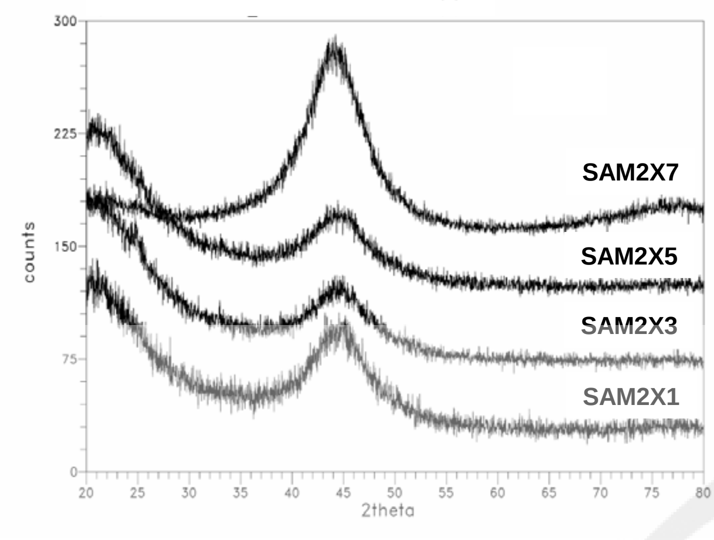


Figure 13 – XRD data for melt-spun ribbons of the Mo-containing SAM2X-series compositions, showing stability of amorphous metal after third neutron irradiation in reactor.

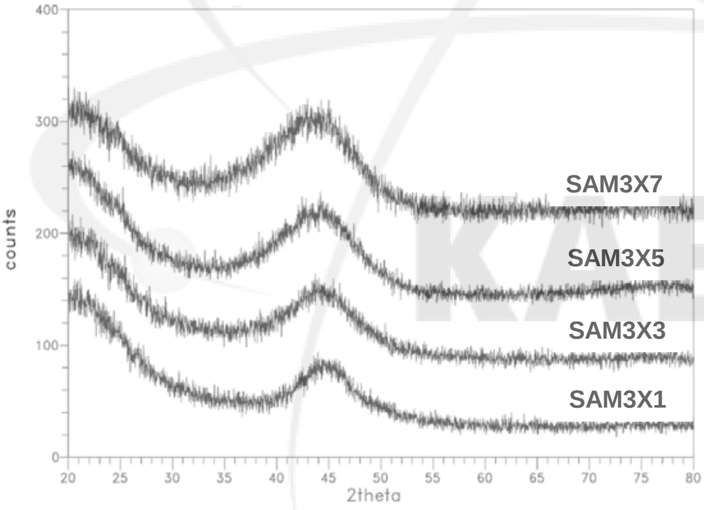


Figure 14 – XRD data for melt-spun ribbons of the Y-containing SAM3X-series compositions, showing stability of amorphous metal after third neutron irradiation in reactor.

4. Transportation, Aging, and Disposal (TAD) Containers

A TAD canister, in conjunction with specially-designed over-packs can accomplish the functions of transportation, aging, and disposal in the management of SNF. The design of the TAD canister would have to enhance, among others, corrosion resistance, thermal stability, and criticality-safety control.

The structural-amorphous-metal (SAM) coatings described above focus on two formulas: SAM2X5 and SAM1651. It is proposed here that the boron-containing, SAM coatings can be applied to the metallic support structure and be used in storage baskets inside the dry storage containers; inside the transportation casks; and inside the disposal containers (TADs) for SNF. These coatings may be:

- thermally-sprayed iron-based amorphous metals with relatively large concentrations of boron;
- any thermal-spray coating with refractory boride particles including, but not limited to the borides of carbon, titanium, chromium, nickel, and other similar compounds; and
- applied by thermal- or cold-spray as a means of joining plates of boron-containing alloys for use in nuclear fuel assembly support structures.

The SAM materials can be enhanced with other neutron poisons beside boron including (a) gadolinium; (b) hafnium; (c) erbium; (d) dysprosium; and (e) cadmium. The materials can also be enhanced with the addition of moderator materials, including (a) carbon; (b) carbides; (c) hydrogen isotopes; and (e) hydrides formed from any of the hydrogen isotopes. The metallic support structural material can be stainless steel, borated stainless steel, or other metallic-based materials (carbon steel, the aluminum-based boron-carbide composites, or the nickel-based gadolinium alloy, etc.).

The use of these durable neutron-absorbing materials to coat stainless steel containers, and storage baskets and racks, as well as vaults, hot-cell facilities and glove boxes could substantially reduce the risk of criticality in the event of an accident. These materials are particularly attractive for shielding applications since they are fire proof.

5. Summary

The high boron-containing, Fe-based amorphous-metal coatings (SAM) coatings can be effective criticality control materials for the TAD containers. The HVOF thermal-spray process is a demonstrated technology to apply the SAM coatings onto metallic alloy substrates.

These Neutron-absorbing SAM coatings are more corrosion resistant than other well-known criticality-control materials, including Al-B_4C composites, borated stainless steels, and Ni-Cr-Mo-Gd alloys. The use of these durable neutron-absorbing materials to coat stainless steel containers and storage racks, as well as steel plates covering the ceiling, walls and floors of hot cell facilities and vaults could substantially reduce the risk of criticality in the event of an accident.

Some Fe-based amorphous-metal formulations have been found to have corrosion resistance comparable to, or better than that of high-performance alloys such as Ni-based Alloy 22. These materials rely on Cr, Mo and W for enhanced corrosion resistance, while B is added to promote glass formation and Y is added to lower the critical cooling rate (CCR).

In the future, such corrosion-resistant thermal-spray coatings may enable the development of less expensive containers for spent nuclear fuel (SNF) and high-level waste (HLW), including the transportation, aging, and disposal containers (TADs). Cost savings can be realized through the substitution of Fe-based alloy for Ni-based materials.

Acknowledgments

This investigative paper was prepared to stimulate the interest that KAERI would research and develop its specific SAM coating materials for the TAD canisters to satisfy the requirements of corrosion-resistance, thermal stability, and criticality-controls for long-term dry storage of high burn-up spent PWR fuel. It is hereby acknowledged that the paper contains referenced information from published work performed by researchers at Lawrence Livermore National Laboratory when the author was a member of the research team.

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APPENDIX

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서지정보양식

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초록 (15-20줄내외)

현재 사용후핵연료의 건식 캐스크는 저장용 또는 저장 및 수송용으로만 개발되어 있다. 장기저장 또는 처분까지도 가능하도록 기능을 확장할 수 있다면 수송, 저장, 처분용 캐니스터의 개발이 가능하다. 이를 위하여 캐니스터의 부식 저항성, 열적 안정성, 임계 안전 제어성이 향상되도록 설계되어야 한다. 본 조사 보고서는 수송, 저장, 처분용 캐니스터에 적용될 비정질 코팅의 개발에 관하여 동경대학교의 Jor Shan Choi 교수의 내용을 요약한 결과이다.

주제명키워드 (10단어내외)	사용후핵연료, 건식 저장, 수송-저장-처분용 캐니스터

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Project Manager and Department (or Main Author)	Yong Soo Hwang
Researcher and Department	

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Abstract (15-20 Lines)

A TAD canister, in conjunction with specially-designed over-packs can accomplish the functions of transportation, aging, and disposal (TAD) in the management of spent nuclear fuel (SNF). Industrial dry cask systems currently available for SNF are licensed for storage-only or for dual-purpose (i.e., storage and transportation). By extending the function to include the indefinite storage and perhaps, eventual geologic disposal, the TAD canister would have to be designed to enhance, among others, corrosion resistance, thermal stability, and criticality-safety control. This investigative paper introduces the use of these advanced iron-based, corrosion-resistant materials for SNF transportation, aging, and disposal.The objective of this investigative project is to explore the interest that KAERI would research and develop its specific SAM coating materials for the TAD canisters to satisfy the requirements of corrosion-resistance, thermal stability, and criticality-controls for long-term dry storage of high burn-up spent PWR fuel.

Subject Keywords (About 10 words)	spent ncuelar fuel, dry storage, TAD canister