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Application of Neutron-Absorbing Structural-Amorphous Metal (SAM) Coatings for Spent Nuclear Fuel (SNF) Container to Enhance Criticality Safety Control

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ACRONYMS

OCRWM	Office of Civilian Radioactive Waste Management
PWR	Pressurized Water Reactor
BWR	Boiling Water Reactor
SNF	Spent Nuclear Fuel
HVOF	High Velocity Oxy-Fuel
QA	Quality Assurance
HPCRM	High Performance Corrosion Resistant Materials
SAM2X5	Structural Amorphous Metal sample series 2X5

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1. PURPOSE

This report describes the analysis and modeling approaches used in the evaluation for criticality-control applications of the neutron-absorbing structural-amorphous metal (SAM) coatings. The applications of boron-containing high-performance corrosion-resistant material (HPCRM) – amorphous metal[1] as the neutron-absorbing coatings to the metallic support structure can enhance criticality safety controls for spent nuclear fuel in baskets inside storage containers, transportation casks, and disposal containers. The use of these advanced iron-based, corrosion-resistant materials to prevent nuclear criticality in transportation, aging, and disposal containers would be extremely beneficial to the nuclear waste management programs.

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2. QUALITY ASSURANCE

The DOE quality assurance program applies to the development of this report. This report is prepared in an AMR-like format in accordance with the DOE/OCRWM/OST&I procedures and Technical Work Plan for: Risk and Criticality.

Computer software results reported in this AMR are example applications of the evaluation developed under this analysis and modeling approaches. References and supporting documents where descriptions of the software, its verification, benchmark and validation, as well as software control procedures are included in the report.

Information and analysis & modeling developed and reported in this AMR-like report is intended to meet the level of detail and accuracy consistent with the DOE Quality Assurance Requirements and Description.

These materials did not involve formal QA as part of the effort; however, good laboratory practice was used as appropriate.

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3. USE OF SOFTWARE

Relevant software for the fuel burn-up and criticality analysis were used. These include ORIGEN and MCNP5, both were obtained from DOE Office of Scientific and Technical Information (OSTI)'s Energy Science and Technology Software Center (ESTSC). Other appropriate software including Microsoft Word, Microsoft Excel, Microsoft PowerPoint, Adobe Acrobat, and Adobe Photoshop was also used.

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4. INPUTS

4.1 DIRECT INPUT

This effort is generating data that is used in evaluating the integrity of metal coatings applied by HVOF subsequent to impact. In preparing the study, potential test cases such as the rock drop from the top of the tunnel (6 ft.) and an accidental crane hook drop (30 ft.) were considered.

4.1.1 INTRODUCTION

Drop tower tests were initiated to determine the resistance of the amorphous metal coatings to impact damage in possible rock drop scenarios or under accidental damage to the coating by handling equipment (drop of a crane hook from 30 ft.). Test results are desired to indicate residual corrosion resistance as well as requirements for repair subsequent to impact damage.

4.1.2 EXPERIMENTAL

An Instron 9250HV impact tester was used for drop testing. The test machine includes a mechanical spring assisted drop system to simulate drops from heights exceeding 30 ft although it is limited in practical sense by the total load that the load cell can tolerate (50,000 lbs). The instrument includes timing mechanisms and data acquisition to acquire load and velocity data during the impact with resolution substantially below 1 millisecond, also called the tupp insert. Because of the relative high effective drop height used in these tests the impact tupp impactor hit the sample multiple times with decreasing energy on subsequent bounces.

Ultrasonic measurements of the reflected energy at the interface between the coating and the Alloy 22 substrate were made with the samples submerged in distilled water. The tests were performed with a focused transducer in the pulse echo mode. Measurements were made with a focused transducer with the transducer located on the substrate side of the sample plate. This was found to be the optimum configuration for minimal noise due to scattering of the sound waves by the fine scale roughness of the surface of the coating. Scans were made at the same settings on all plates before and after the impact tests. Confirmatory ultrasound measurements were made on the samples and the substrates to obtain confidence in the measurements. In particular ultrasound measurements upon a corner of the Alloy 22 plate (MS17S1) where the SAM2X5 coating was completely ground off indicated that a 100% energy reflection was obtained in the case of complete dis-bondment (or absence) of the coating. In this series of tests some variability, which is attributed to the substrates, was observed; however, the relative differences of a given plate before and after impact testing were readily obtained.

4.1.3 RESULTS

Figure 1. This is an optical photograph of plate M17S1. All impacts were made at the same velocity, drop weight, and with the same 0.5” diameter spherical impactor. The plate appeared to have some variability from side to side based on Ultrasonic NDE measurements shown in Figure 2. Also in general, this plate (M17S1) appeared to have noticeable differences in the magnitude of reflected energy from the interface between the coating and substrate when measured under the same conditions as the other plates. The drop conditions are shown in Table 1 below. Note that rust spots on the left hand side are due to a steel angle iron used to hold the plate in the water tank used for Ultrasonic NDE.

Table 1. Drop conditions and results for Plate M17S1.

Plate M17S1

Impact #	Tupp insert dia. (in)	Impact Velocity (ft/sec)	Drop Wt. (lb)	Max. Load (lb)	Total energy (ft-lbf)
1	0.5	29.68	16.03	30479	183.09
2	0.5	29.59	16.03	29475	185.26
3	0.5	29.56	16.03	28279	188.75
4	0.5	29.54	16.03	31300*	171.57

Notes: *Load signal exceeded tupp capacity, estimated peak load is shown.
*Tupp insert fractured near the tip radius
*Possible intermittent load signal from cable; an estimate of Max Load is included

Figure 3. This image shows the Ultrasonic NDE measurement of plate M17S1 before impact testing. The corner in the upper right was intentionally surface ground down to the level of the Alloy 22 substrate to reveal the amount of energy reflected by a completely unbonded coating. This particular plate appeared to have more variability as observed by the slight color difference at the bottom right and upper right. Note that the edges (~1/4") of the plate should be ignored since a focused transducer was used which is affected by edges of the substrate. Also the signal results in this figure have been mirrored appropriately so that the positions of the impacts can be identified in the associated optical photograph. This is required because the ultrasound measurements are taken from the back of the plate.

Figure 3. This figure shows plate M17S1 after impact testing. The slight yellow lines reflect cracks observed in some cases on the surface. The large white areas are regions where greater reflected energy is observed at the interface. For these impacts at nominally 9m/s the "white areas" are much larger than in plates M17S3 and M17S4. Note that the edges (~1/4") of the plate should be ignored since a focused transducer was used which is affected by edges of the substrate. Also the signal results in this figure have been mirrored appropriately so that the positions of the impacts can be identified in the associated optical photograph. This is required because the ultrasound measurements are taken from the back of the plate.

Figure 4. This is an optical photograph of plate M17S3. The drop conditions are shown in Table 2 below.

Table 2. This table shows tests conditions and results for Plate M17S3 shown in Figure 4.

Plate M17S3

Impact #	Tupp insert dia. (in)	Impact Velocity (ft/sec)	Drop Wt. (lb)	Max. Load (lb)	Total energy (ft-lbf)
1	0.5	9.97	16.35	8563	23.37
2	0.5	9.98	16.35	8500	23.28
3	0.5	9.95	16.35	9462	22.63
4	0.5	19.13	16.19	20146	76.11
5	0.5	19.16	16.19	20220	76.61
6	0.5	19.29	16.19	20567	78.22
7	0.5	29.73	16.19	31688	183.55
8	0.5	29.65	16.19	30720	183.13
9	0.5	29.58	16.19	33021	182.84
10	0.5	42.57	16.15	43000*	286.70
11	0.5	43.14	16.25	42000*	309.91
13	0.5	19.69	27.76	30306	144.16
14	0.5	19.69	27.76	29917	145.64
15	1.0	19.11	16.61	19684	84.51
16	1.0	19.22	16.61	20638	84.88

*Note: load cell signal lost during a portion of the impact, the most likely estimated peak load is shown.

Figure 5. This image shows the Ultrasonic NDE measurement of plate M17S3 before impact testing. This particular plate appeared to have some variability as observed by the moderate reflected energy change going from right to left. A more extreme difference is noted in the green region in the upper left corner. Note that the edges (~1/4”) of the plate should be ignored since a focused transducer was used which is affected by edges of the substrate. Also the signal results in this figure have been mirrored appropriately so that the positions of the impacts can be identified in the associated optical photograph. This is required because the ultrasound measurements are taken from the back of the plate.

Figure 6. This figure shows plate M17S3 after impact testing. The slight yellow lines reflect cracks observed in some cases on the surface. The large areas with colors above red and yellow on the scale are regions where greater reflected energy is observed at the interface. A transition to greater reflected energy at the interface for the impacts on the left hand side of the plate is observed. The larger regions of higher reflected energy around the impacts appears to be consistent with the before impact Ultrasonic NDE measurements. Note that the edges (~1/4”) of the plate should be ignored since a focused transducer was used which is affected by edges of the substrate. Also the signal results in this figure have been mirrored appropriately so that the positions of the impacts can be identified in the associated optical photograph. This is required because the ultrasound measurements are taken from the back of the plate.

Figure 7. This is an optical photograph of plate M17S4 after impact testing. More significant coating detachment appears to occur where impacts are relatively closer together or the impact is close to an edge. More intense localized damage does occur near the impact point. Note that rust spots in the lower left corner are due to a steel angle iron used to hold the plate in the water tank used for Ultrasonic NDE.

Plate M17S4

Impact #	Tupp insert dia. (in)	Impact Velocity (ft/sec)	Drop Wt. (lb)	Max. Load (lb)	Total energy (ft-lbf)
1	0.5	9.94	16.31	10171	22.47
2	0.5	19.19	16.31	20493	79.86
3	0.5	29.76	16.31	32195	190.63
4	0.5	44.11	17.17	45169	465.13
5	0.5	19.69	27.68	29313	145.85
6	0.5	19.79	27.68	29593	150.64
7	0.5	19.7	27.68	29105	147.94
8	0.5	9.98	27.68	15034	39.21
9	0.5	9.99	27.16	15275	37.79
10	0.5	9.97	27.16	15484	37.54
11	1.0	18.96	16.6	20563	83.48
12	1.0	19.27	16.6	22749	84.90
13	1.0	19.11	16.6	22567	83.13
14	1.0	9.92	16.6	11104	23.53
15	1.0	9.95	16.6	11213	23.59
16	1.0	9.9	16.33	11266	22.55

Figure 8. This image shows the Ultrasonic NDE measurement of plate M17S4 before impact testing. This plate showed reasonable uniformity although a subtle vertical shadow in the middle of the plate may reveal an area of relatively thinner coating. Note that the edges should be ignored since a focused transducer was used which is affected by edges of the substrate. Also the signal results in this figure have been mirrored appropriately so that the positions of the impacts can be identified in the associated optical photograph. This is required because the ultrasound measurements are taken from the back of the plate.

Figure 9. This figure shows plate M17S4 after impact testing. Some overlap of impacts appears to be present. Also the small vertical patch of yellow green along with the purple/blue vertical streaks through some of the white patches surrounding impacts in the middle of the plate are possibly related to thinner coating in that region (this was observed in Figure 8). Note that the edges (~1/4") of the plate should be ignored since a focused transducer was used which is affected by edges of the substrate. Also the signal results in this figure have been mirrored appropriately so that the positions of the impacts can be identified in the associated optical photograph. This is required because the ultrasound measurements are taken from the back of the plate. Note a slightly different scale is used in the figure (compared to Figure 9) to highlight contrasts.

4.2 CRITERIA

Results that were consistent with realistic physical phenomena were considered.

4.3 CODES, STANDARDS, AND REGULATIONS

No codes, standards, or regulations of direct applicability are known to exist; however, some may be in the process of being developed by the HPCRM project team.

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5. ASSUMPTIONS

As this initial work is with hybrid nanocomposite coating materials, conclusions drawn from this study rely on an uncertain assumption that amorphous coatings will behave in a comparable manner. This is not necessarily assumed to be appropriate at this point, but these materials were a reasonable starting point for this activity. The test parameters for these experiments are made with consideration of the potential impact situations for a container (rock drop or accidental crane hook drop as noted earlier). However, no calculations, comparisons, or simulations have been performed to date to determine what stress state might exist under impact conditions for rocks or a crane hook. Details of a simulated rock or hook are unavailable or undefined at present. Further the choice of 0.5" and 1" spherical radius for the impactors is quite possibly of a much greater radius of curvature than might be expected. Comminution of the rock during an impact would likely lessen stress states. A steel impactor does not allow for simulation of comminution during impact. In actual conditions, the mass of the object impacting the coating will be much greater. The offsetting effects of the impactor radius of curvature and the mass of the impacting object are unknown at present.

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6. MODEL DISCUSSION

It is apparent that differences among the coated plates that were tested. In particular there were differences in the response of the interface between the coating and the substrate from plate to plate for the same test condition (see Table 4). Particularly this was present in plate MS17S1 compared to MS17S3 and MS17S4. In the case of plate M17S1 the area disturbed by the impact as revealed by ultrasonic reflected energy. There were secondary differences between MS17S3 and MS17S4, but the differences appeared to be of lesser extent.

Table 4. This table compares the extent of the change in the properties of the interface adjacent to impacts as measured by ultrasound NDE. In particular plate M17S1 showed a significantly larger area affected by the impact. These measurements were at 9m/s, ~16 lbs. load, and utilized a ½" spherical impactor.

Comparisons between plates 3, 4 and 1:
9m/s low load 0.5" impactor

Velocity m/s	**Avg Velocity (m/s)**	**Impact Velocity (ft/sec)**	**Drop Wt. (lb)**	**Max. Load (lb)**	**Total energy (ft-lbf)**	**Plate**	**Impact Max Extent (inches)**	**Area (inches^2)**
9	9.0	29.59	16.0	29883.3	182.2	MS17S1	2.38	4.59
9	9.0	29.65	16.2	31809.7	183.2	MS17S3	1.41	1.56
9	9.1	29.76	16.3	32195.0	190.6	MS17S4	1.45	1.65

In general it was observed that greater velocity led to larger diameter of the region were the ultrasonic reflected energy was increased at the coating/substrate interface (see Table 5). This is reasonable considering the extra energy delivered by the higher velocity impact. However, it is not certain that in all cases this represents breaking of the bond between the coating and substrate. It is apparent that in the lower velocity impacts (e.g. 3 and 6 m/s) produce less significant damage to the coating and often it appears that the coating layer remains substantially intact (see low velocity, low load impacts in Figures 4 and 7). This is more particularly true in the case of the 3m/s impacts at the lowest load used in the study.

The tests with higher load and the 1" spherical impactor (in contrast to the ½" spherical impactor) were not completely conclusive given the small data set and the slight differences between plates M17S3 and M17S4. In general it appeared that the areas of increased reflected energy surrounding the impacts were larger in M17S4 compared to M17S3 for all other conditions being equal. The 1" diameter impactor produced slightly higher peak loads (~15%) possibly because the larger radius of curvature increased the area of physical contact during impact at a much faster rate than with the ½" diameter impactor. Although the data set is small it appears that the higher loads and the 1” diameter impactor increase the area of the interface that is affected by the impact.

In general this study so far suggests that ultrasonic NDE is a technique that can potentially be used for quality control on coatings and as an analytical tool to help determine extent of repair that may be needed for coatings damaged by operating conditions. As part of this study it is evident that future work will require careful separation of impact points to minimize the effect of adjacent impacts. Potentially, destructive measurements using cross-section metallography would be beneficial to confirm some of the observations made using NDE. Further study will involve salt fog testing of the tested plates along with comparable untested plates.

Table 5. This table summarizes average measurements for the impacts on the SAM2X5 coated Alloy 22 plates. It does not distinguish between plates that may have had relatively poorer interface between the coating and substrate such as M17S1 and therefore some trends are not as apparent.

Low Load 1/2" spherical impactor

Velocity (m/s)	Avg Velocity (m/s)	Impact Velocity (ft/sec)	Drop Wt. (lb)	Max. Load (lb)	Total energy (ft-lbf)	Impact Max Extent (inches)	Area (inches^2)
3	3.0	9.96	16.3	9174.0	22.9	0.86	0.69
6	5.8	19.19	16.2	20356.5	77.7	1.29	1.33
9	9.0	29.64	16.1	30894.6	183.6	1.90	3.08
12.3	13.2	43.27	16.5	43389.7	353.9	1.75	2.55

High Load 1/2" spherical impactor

Velocity (m/s)	Avg Velocity (m/s)	Impact Velocity (ft/sec)	Drop Wt. (lb)	Max. Load (lb)	Total energy (ft-lbf)	Impact Max Extent (inches)	Area (inches^2)
3	3.0	9.98	27.3	15264.3	38.2	1.84	2.69
6	6.0	19.71	27.7	29646.8	146.8	1.47	1.75

Low Load 1" spherical impactor

Velocity (m/s)	Avg Velocity (m/s)	Impact Velocity (ft/sec)	Drop Wt. (lb)	Max. Load (lb)	Total energy (ft-lbf)	Impact Max Extent (inches)	Area (inches^2)
m/s							
3	3.0	9.92	16.5	11194.3	23.2	1.12	0.98
6	5.8	19.13	16.6	21240.2	84.2	1.50	1.81

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7. VALIDATION

Attempts were made to validate ultrasonic measurements using measurements on machined surfaces of the nickel alloy substrates. The measurements of reflected energy with the coating removed were used as calibration points for setting the full scale maximum on the reflected energy scale. This scale maximum was set to obtain high resolution and does not reflect the full energy supplied to the plates by the transducer. The load cell for the drop tests was calibrated and met specifications for the testing.

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8. CONCLUSIONS

Impact testing on the hybrid nanocomposite coating applied to Alloy 22 substrates was performed. Ultrasonic NDE techniques were shown to be useful in evaluating changes in the interface surrounding impact points. It appears that Ultrasonic NDE techniques may be useful to check for quality assurance. Some variability in coatings was observed in this study based on the amount of reflected energy measured for the coating to substrate interface in the 3 plates that were tested. It was also observed that when greater amounts of reflected energy at the interface are observed using ultrasonic NDE prior to the impact test, the extent of the affected interface around the impact site is increased. With low load testing (16 lbs), the 3m/s impacts did not appear to produce substantial damage to the coating beyond local indentation. At 6m/s the local deformation was larger but generally fracture of the coating was limited. At larger velocity (9m/s and above) more significant damage including some cracking and loss of coating was observed. The ultrasonic NDE measurements for particularly the larger velocity impacts suggest that a larger sub-surface region than just the visible damage areas may need to be repaired to bring the coating integrity back to its original condition. Larger loads and to a lesser extent a larger spherical impactor radius appeared to increase the affected interface area, but further study will be needed to accurately assess this result.

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9. INPUTS AND REFERENCES

9.1 DOCUMENTS CITED

(Style Manual, References, Documents Cited)

9.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

(Style Manual, References, Codes, Standards, Regulations, and Procedures)

9.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

(Style Manual, References, Data)

9.4 SOFTWARE CODES

(Style Manual, References, Software Codes)

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