The Effective Use of Tungsten as a Shielding Material in Nuclear Applications

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Executive Summary

In looking beyond conventional materials such as lead, steel, and water for more effective materials to use in shielding applications at nuclear facilities, tungsten has been identified as a viable radiation shielding material. Possessing superior shielding factors versus lead while removing the accompanying toxicity hazard and mixed waste processing costs, tungsten has shown that it can be effectively and economically utilized in large-scale shielding applications.

The most effective utilization of tungsten, in one of its many forms, will be achieved after evaluation of several key factors (space / environmental considerations, long-term storage / disposal, and potential for multiple applications) on the prospective application. Though not cost-beneficial for "ordinary" shielding applications, when properly selected as the shielding material, dose avoidance exceeding that of lead will be achieved.

Tungsten Facts and Figures

Tungsten (symbol: W) is number 74 on the periodic chart of the elements, appearing in a grouping of high-density metals that include iridium, platinum, and gold. With a density of 19.25 g/cc, it is one of the densest naturally occurring elements. Tungsten's origin is traced to the cooling of magma that has penetrated the Earth's crust and the primary deposits are found in the "younger" mountain ranges such as the European Alps, the Himalayas, and the Pacific Rim. Currently, approximately 75% of all processed tungsten comes from China.

In its pure form, tungsten is a grayish-white, lustrous metal. Its most common naturally occurring state is that of WO_3 (tungsten trioxide). The etymological origin of tungsten stems from the Swedish "tung-sten" meaning "heavy stone." The somewhat unusual elemental symbol of "W" derives its origin from wolfram which in turn is from the German "wolfrahm" meaning "wolf froth" which was the colloquial moniker provided by tin miners to describe the way its ore would tear away tin during reduction processing "like a wolf devours sheep."

Uses for tungsten include filament material for electric lamps, electron and television tubes, X-ray targets, windings and heating elements for electrical furnaces, high-speed tool steels and many other alloys. Tungsten has also been used in limited applications in the nuclear industry as a shielded probe material. Given that the application had already been identified, the next logical progression would be use as a physical shielding material for maintenance activities in the nuclear power industry.

Why Use Tungsten?

Similar to lead (Pb), tungsten possesses a high density (19.25 g/cc) and pliability in its metal state. Where tungsten gains the advantage is in the ease of blending into plastic for extrusion or molding into custom shapes and sizes. Tungsten also differs from lead in that it is virtually non-reactive and is non-toxic. This eases handling requirements and minimizes issues associated with lead use such as long-term disposal and the potential characterization as a mixed hazardous waste.

Tungsten also exists in sufficient, available quantities as to be a viable shielding material and, while more expensive than lead or steel, the cost differences are not prohibitive.

The table below provides a more detailed comparison of tungsten and lead and their shielding properties (Figure 1).

Criteria	**Tungsten (W)**	**Lead (Pb)**
Density	19.25 g/cc	11.34 g/cc
Cost	~$12 per pound	~$4 per pound
Tenth-Factor Thickness	~1 inch	~2 inches
Shielding Factor	10x Lead in metal form 1.16x Lead in plastic pellet form	1x Lead in metal form 0.16x Lead in blanket form
Blending	Easily blended in plastic	Some impregnating in rubber
Re-use	Reusable	Reusable
Disposal	Normal	Potential Mixed Hazardous Waste
Toxicity	Non-Toxic	Toxic - handle with gloves
Space Considerations	Similar load issues to pure lead applications	Bulky in blanket form, loading restricted in pure forms

Figure 1. Tungsten versus Lead: Head to Head Properties Comparison

Given the availability, low-cost, and inventory of lead shielding at nuclear facilities, wholesale replacement of lead with tungsten is not practical or effective. Effective use is dependent on the circumstances and environment surrounding the individual installation. Tungsten is not necessary for the majority of standard applications where a layer of conventional lead blanket will provide the desired dose rate reduction.

The value of tungsten shielding is shown when unique applications, or “outside the box” thinking, is required.

Key Factors in the Selective Use of Tungsten

The differences between tungsten and lead provide the opportunities to address more creative shielding needs. These differences are the drivers for two out of the three key factors to consider.

1. Space and Environmental considerations
    - The tenth-value thickness for tungsten is approximately one-half that of lead allowing for greater dose rate reductions in smaller spaces
    - Effective for use where there are narrow clearances or space limitations (for example: substituting a five (5) inch pellet shield wall versus thirty (30) layers of lead blanket
    - Underwater applications (where use of lead wool blankets is not advised)

2. Long-term storage / disposal
    - Not a potential mixed hazardous waste - far less costly to dispose of at the end of a facility’s life
    - Less toxic - ease in handling in pellet form versus lead shot

3. Potential for multiple applications
    - Recognizing multiple applications for the tungsten shielding (as for any engineered control) enhances the cost / benefit analysis for use of the material
    - Several viable forms of tungsten shielding technology already exist, with additional research and production in progress

As the nuclear industry continues to “clean” up, both in terms of RadWaste processing / burial and in decommissioning, purchase and use of additional lead shielding will become less attractive. Tungsten can play an effective role in shielding plans, offsetting large-scale use of lead (in shot or blanket form).

Successful Applications

Two shielding applications are discussed in the following section. Each highlights a variation on the use of tungsten and demonstrates where significant results can be achieved in exposure reduction.

Challenge #1: Quad Cities-2 Condensate Demin Modification

As part of the Quad Cities station Extended Power Uprate (EPU) project, an additional Condensate Demineralizer was required for the increased power levels. The radiological challenge presented by this modification was the gross number of construction person-hours (several thousand person-hours) required in an area that is normally controlled as a Locked High Radiation Area (LHRA).

Dose rates could be reduced effectively through securing the adjacent Demin unit, but at a cost of potential plant de-rates and reduced capacity factor. The desire to maintain the adjacent Demins on-line (and ranging from 200-800 mrem/hour) necessitated extensive shielding. To complicate the planning, a 2.5 foot thick concrete wall would be removed that would normally serve as shielding.

The new Demin unit would occupy a space allowing for only five (5) inches of clearance from the adjacent sources. This restricted work space, coupled with the loss of 2.5 feet of concrete shielding, was too small to permit a sufficient amount of lead blanket shielding to achieve the 0.5 mrem/hour dose rate established as a project goal.

Several other factors were identified for the shielding application. These included:

- Weight allowances (floor loading restrictions)
- Flammability concerns (due to extensive welding as a part of the modification)
- Ease of installation / removal (removal of shielding once the new vessel was installed)

In evaluation against traditional lead shielding and water shielding technologies, the use of tungsten-impregnated plastic pellets was selected for the application for several reasons.

1. The project required a solution that would achieve working dose rates of 0.5 mrem/hour or less with the existing LHRA starting conditions
2. Tungsten provided a five (5) inch shield wall solution versus thirty-plus (30+) layers of lead blanket shielding (meeting the 5 inches of clearance requirement versus the 30 inches effectively required for the blanket)
3. Lead pellets/shot would represent purchase of 24,780 pounds of raw lead that would be a long-term liability to the station
4. Even diluted in plastic, tungsten's shielding properties for Co-60 gamma energy levels exceeded lead (116% reduction versus same thickness of lead)
5. Initial costs would be off-set by multiple planned applications (including the same modification on the second Quad Cities unit)

After the selection of tungsten-impregnated plastic was made, the material was procured and poured into three five-inch thick, reinforced tanks which were stacked to create the shield wall between the existing Demin and the location of the new Demin to be installed. Once in place, and with the other Demins in their operational configuration, the 0.5 mrem/hour dose rate goal established for the project was met and the modification was completed as planned. The resulting dose reduction of the tungsten shield is shown in Figure 2.

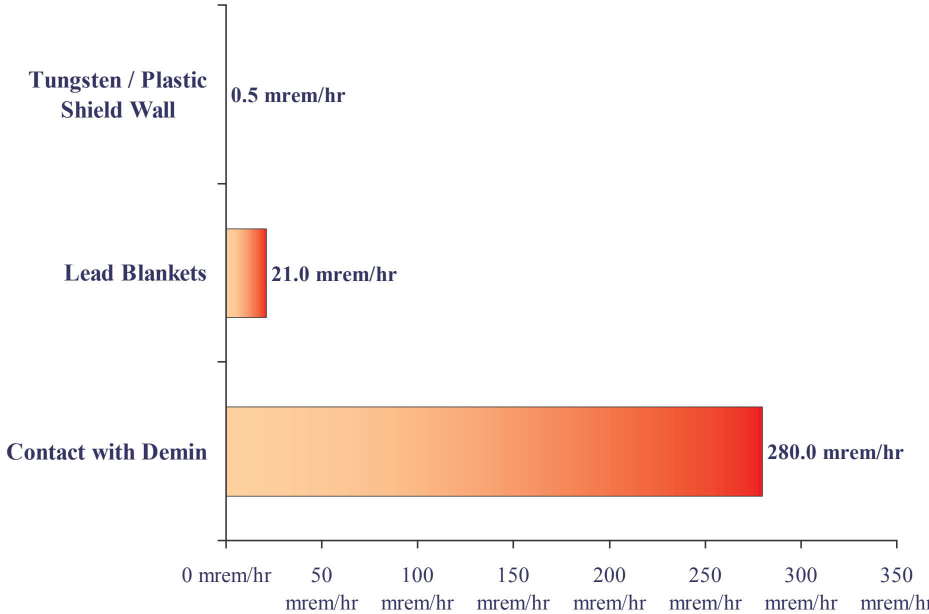

Figure 2. Tungsten Dose Rate Reduction versus Lead Blanket for the U2 Cond Demin Mod

Based on the dose reduction results seen with the tungsten pellet application, 30.3 person-rem were avoided versus the use of lead blanket shielding. The overall project was completed for a total dose of 3.3 person-rem.

As per the original project planning, the same successful method was applied to the sister modification on unit one with even greater results due to the dose rate differences between the units. The Quad Cities-1 project avoided 91.0 person-rem and was completed for a total dose of 7.2 person-rem.

Challenge #2: Quad Cities-1 Steam Dryer Underwater Weld Repair

As a result of lessons learned from the Quad Cities-2 EPU, a modification would be performed on the Steam Dryer Side Plate during the Q1R17 refueling outage. This required modification presented the challenge of underwater welding and dive operations adjacent to a 10 rem/hour source (the Steam Dryer itself). The clearance available for shielding the divers from the Steam Dryer was three (3) inches after which, additional shielding would interfere with welding or require removal of shield plates from the work area.

When this modification had been performed on Quad Cities-2, three-inch steel plates were used for shielding providing a 4.3x factor reduction. This reduction factor would be insufficient for Quad Cities-1 due to the elevated radiological conditions on this unit.

The project would also have the further constraint of year-end accumulated diver dose nearing regulatory approved levels. This limited dose available for skilled diver/welders combined with end-of-year annual limits had to encompass the completion of diving activities at both Quad Cities-1 and Dresden-3 in the fourth quarter of 2002.

Three shielding materials (lead, steel, and tungsten) were evaluated to determine the most effective means of accomplishing the dose reduction required to complete all work activities at the two units. Tungsten, in its pure, powdered form, was selected due to its superior tenth-value thickness and small clearance available. A two-inch solid thickness of tungsten was encased in one-quarter inch steel plates creating a shield plate that had an overall thickness of 2.5 inches, thereby staying within the space restrictions.

The dose rate reductions achieved using the steel-cladded tungsten plates, as well as the dose rates expected through the use of steel plates alone (based on Quad Cities-2 experience), are shown in Figure 3.

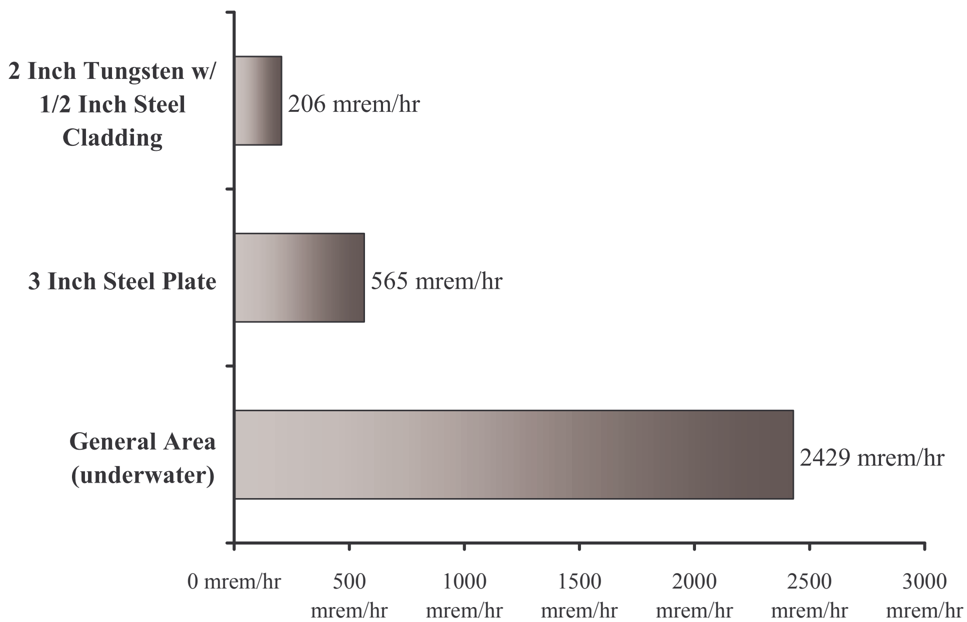

Figure 3. Tungsten Plate Shielding Resulting Dose Rate for Quad Cities-1 Steam Dryer Diving Activities

The 2.5 inch shielding plates comprised of tungsten metal powder encased in steel cladding provided a reduction factor of 11.8x versus a reduction factor of 4.3x for the three-inch steel plate thus enabling the all work activities to be completed at both units within the available dose of the skilled diver crew.

Overall savings for the tungsten plate shields at Quad Cities-1 were calculated at 141.1 person-rem. Realistically, had the tungsten option not been selected, the work would have been completed with the existing three-inch steel plate shielding. Measured against that alternative, the tungsten plates avoided 21.9 person-rem above what would have been saved by steel shielding alone.

These plates were also used at Dresden-3 in the fourth quarter of 2002 for a dose avoidance of 18.6 person-rem and will be used for the final Steam Dryer modification in the series at Dresden-2 in 2003.

Future Directions

With each of the originally designed-for applications completed, the tungsten utilized in the successful Quad Cities applications is available for additional shielding opportunities at Quad Cities and other sites. Several current applications are under development including the Dresden-2 Steam Dryer Modification (plates), shielding of irradiated in-core detectors (pellets), and RWCU system small bore line shadow shielding (plates).

Additional research is going into development of extruded tungsten/plastic “tape” that can be easily wrapped around piping and rubber encasing of tungsten for custom-formed pipe shielding.

Concluding Remarks

The use of tungsten as a shielding material, in many forms, can significantly reduce exposure for maintenance and modification activities at nuclear generating stations. Several key factors must be evaluated to ensure effective use of tungsten versus existing, conventional shielding materials. These are:

- Space and Environmental considerations
- Long-term storage / disposal
- Potential for multiple applications

The effective addition of tungsten to the dose reduction arsenal is dependent on sound economics and an understanding of the solution required to achieve the dose reduction goals that have been determined. When the appropriate application has been identified, tungsten shielding will do the job and do it successfully.