Eliminating Cold-Shut Defects in Deep, Single-Pass, Electron Beam Welds in Uranium

Shims are melted into the weld metal to lower the solidification temperature and thereby prevent the formation of cold-shuts

BY D. H. WOOD AND G. L. MARA

ABSTRACT. A technique for avoiding cold-shut defects in deep, single-pass, electron beam welds is described and evaluated. Shims of an appropriate alloying metal are interleaved in the joint before welding, and during the welding process, the shim is melted and mixed into the weld metal, lowering the solidification temperature and thus preventing the formation of cold-shuts. For uranium and some of its low-dilution alloys, the shim may be made of copper.

Introduction

The phenomenon of cold-shut defects in the root of deeply penetrating electron beam welds was observed at least ten years ago. As early as 1966, the problem was well documented by Groves and Gerken[1] for four different alloys. Single-pass electron beam welds are still used because they are the cheapest welds in terms of joint preparation and machine time and because they cause minimum distortion. Until now, the cold-shut problem has been ignored because mechanical strength requirements have not been rigorous, or it has been avoided by changing the joint design. Concurrently, a somewhat confusing situation has developed in the nomenclature used to describe cold-shuts and related phenomena.

The term cold-shut has been used for many years to describe a defect in castings. For the purposes of this paper, the term cold-shut is used to identify a type of incomplete fusion. A cold-shut can be defined as a thin, usually cone-shaped void or incomplete fusion defect found in the root and sometimes also in the upper regions of an electron beam weld. Its cause is much the same in a weld as in a casting. Microcracking and hot cracking are distinctly different from cold-shuts, although they sometimes occur together.

A good picture of cracks and cold-shuts has been provided by Boolen[2] who uses the term "root voids" to include a defect that we would call a cold-shut. Spike is another common word describing a point of extra deep beam penetration, and since cold-shuts frequently occur where there has been spiking, there is a tendency to confuse these two independent phenomena. Armstrong[3] has published some excellent pictures showing relationships between cold-shuts and spikes.

In this paper, we describe a series of experiments performed to evaluate the hypothesis that cold-shut defects can be eliminated by interleaving a shim in the weld joint.

The Hypothesis

In an electron beam weld, pool surfaces are created by the beam penetration. Cold-shuts are caused by low fluidity from lack of superheat in the weld pool such that the metal surface, while flowing into the mold, cools to a point at which no mixing or fusion can occur. Sometimes the surface even solidifies before the streams come together.

It has been observed that the liquid metal in the region of a cold-shut collapses toward or against the previously solidified wall of the weld cavity. This liquid must therefore have lacked sufficient superheat for fusion, i.e., it must have been close to its solidification temperature. The electron beam is only occasionally present in the lower portion of the cavity and, therefore, pool surfaces often collapse against relatively cold walls. The result can be that no mixing or welding takes place at the interface.

As has been observed, the molten metal may even solidify before it completely fills in against the cavity wall, giving rise to a type of cold-shut referred to as a "necklace-type defect." This observation reinforces the idea that just prior to the formation of cold-shut, there is little superheat in the adjacent molten metal.

Uranium and many of its alloys are known to have high fluidity in the weld pool. There was little we could hope to do to increase this fluidity. However, it did seem possible to extend the time to freezing. It was reasoned that, if we could delay the solidification of this submerged fluid surface—or in other words provide an effective superheat—we could prevent cold-shuts from forming.

Thinking of a binary phase diagram showing a low melting eutectic as the first alloying feature, we speculated that the addition of a small amount of the right alloying element during the welding process could enhance the effective superheat by making the melting point lower on cooling than during melting. We reasoned that placing a thin shim of alloying metal in the weld joint would not change the amount of energy delivered by the electron beam or the temperature of the metal in the weld pool, and perhaps not even the fluidity.

If these assumptions were true, using a properly selected shim would provide more time to solidification and thus alleviate or reduce the cold-shut problem.

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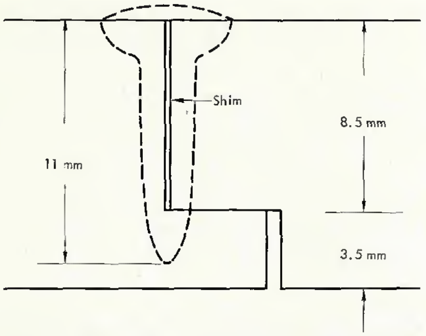

Fig. 1—Typical weld geometry used in the first experiment, shown with exaggerated shim thickness and dashed lines to indicate the fusion zone in the completed weld

Table 1—Results of Visual Examination of Welds from the First Experiment

Shim	Thickness of shim, mm	Number of cold-shuts found above the step	Remarks
Control	no shim	8	No porosity.
Nichrome	0.14	None	Porosity; cracked.
Platinum	0.13	None	Sound except for cracks.
Rhodium	0.18	1	Some porosity.
Gold	0.13	7 or 8	Cold-shuts are smaller; different from control.
Nickel	0.13	None	Porosity; cracked.
Hiperco	0.13	None	No porosity; very brittle.

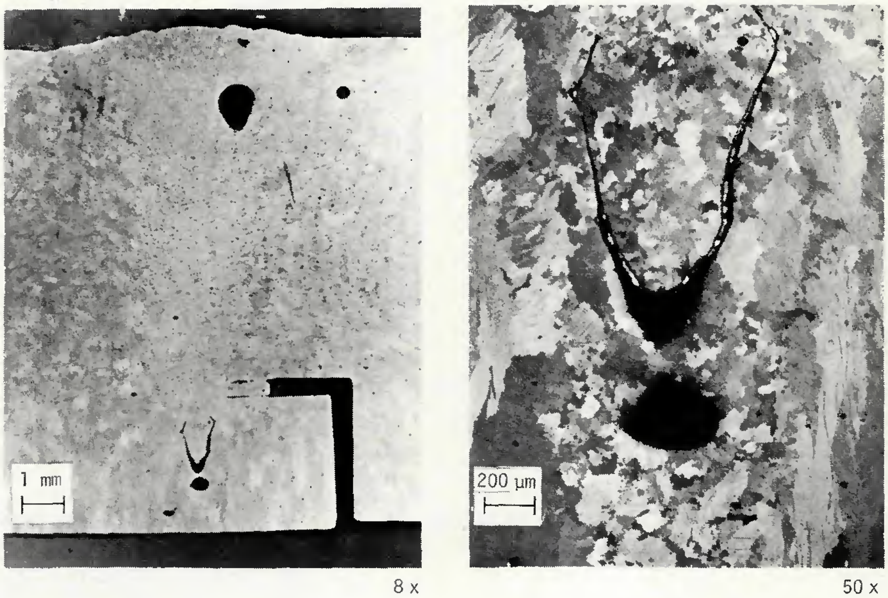

Fig. 2—A classical cold-shut, a root void, and a weld pore shown in a random cross section in a control weld made in U-0.3 wt% Ti alloy using no shim. No other sections were polished. The cold-shut below the step would not have been seen or counted in the data listed in Table 1

The Experimental Program

We carried out several experiments welding uranium and uranium low-titanium alloys. Our first experiment used shims of metals having considerable solid solubility in uranium to lower the melting point. The shims were prepared from Nichrome (85Ni-15Cr), platinum, rhodium, gold, nickel, and Hiperco 50 (49Fe-49Co-2V) in the 0.12 to 0.17 mm thickness range.* They were cut just wide enough to fill the full depth of the prepared joint, as shown in Fig. 1.

No attempt was made to optimize parameters for each weld on the Hamilton-Standard** electron beam welding machine. We used parameters previously established for this joint in U-0.3 wt% Ti (125 kV, 31 mA, 12.7 mm/s, with a spot size of 0.89 mm). The plates were gamma-quenched castings of U-0.3 wt% Ti alloy prepared for us by National Lead Co. of Ohio. A weld without a shim was made as a control.

The resulting welds were generally brittle. All, except the control weld and the one containing gold, cracked along the centerline without load. The two that did not crack were broken in three-point bending (the specific loads were not measured). The results of an examination of the seven broken welds are shown in Table 1. Figure 2 shows a random cross section of the control weld.

Our experiment confirmed that shims can prevent the formation of cold-shuts. There was a correlation between the magnitude of the change in melting point (difference between the eutectic temperature and the melting point of uranium as estimated from binary phase diagrams) and the number of cold-shuts found in the welds above the step.

The control weld had eight classical cold-shuts. The weld with the gold shim (28 C or 50 F drop to the eutectic) had several small defects, apparently cold-shuts. Of the others (all of which had mushy regions of over 100 C or 180 F), only the one with rhodium had even a single cold-shut visible in the fracture. From the Rh-U phase diagram[4] it would appear that only about 100 C of the mushy region would be available unless there was extreme segregation in the alloy. The amount of mushy region available is a function of the solubility of the shim metal in the uranium.

We concluded that high shim solubility is bad for two reasons: first, most soluble elements embrittle the weld and lead to cracking; second, as with rhodium in our experiment, solubility can restrict the useful portion of the temperature drop to the eutectic.

We searched the literature for elements with little or no solubility in uranium that would provide a lowering of the melting point. Copper (with a drop of 52 C or 93.6 F to the eutectic) and yttrium were selected as shim materials to be tested in a second experiment.

The welds were made and evaluated this time exactly as in the first experiment. Upon breaking them, we noticed that the yttrium shim had not completely dissolved. Spherical globules and sheets of yttrium were visible, indicating that there had been too much of this metal present, but there were no cold-shuts. A smaller piece of yttrium placed closer to the surface might have melted completely. The copper, on the other hand, seemed evenly distributed and could be seen in the form of little colored globules in a polished section. According to the phase diagram, this globular copper-rich phase should be the intermetallic, UCu_5. Both of these plates broke in three-point bending at approximately the same force.

The strength exhibited by these two welds, the lack of cold-shuts, and the complete lack of cracking confirmed

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We use SI units in this paper. To convert mm to in., divide by 25.4; to convert kg to lb, divide by 0.453; to convert MPa to ksi, divide by 6.894.

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that copper and yttrium are candidate shim materials in uranium welding. However, because of the relative difficulty of preparing small thin sheets of yttrium, it was decided to concentrate our efforts on copper.

The third experiment used a single, somewhat thicker plate of U-0.75 wt% Ti alloy that had been arc melted, hot rolled, and water quenched from 850 C (1562 F) at the Bureau of Mines, Albany, Oregon. The composition of this material was reported as:

Ti	0.76 ± 0.01 wt%
C	(top) 92 ppm
	(center) 48 ppm
	(bottom) 59 ppm
Fe	20 ppm
Cu	10 ppm
Ni	50 ppm
Si	10 ppm

The geometry of this weld joint is shown in Fig. 3. After removal of a sample for metallographic examination, this weld was 120 mm long. A sharp 2 mm deep notch was milled down the center of the weld bead, and the plate was inverted and broken in three-point bending using an approximate span of 70 mm. It supported a load of 100 kg. Although it is possible that there were undetected cold-shuts below the step, none were observed in the broken section.

A photograph of a randomly chosen transverse cross section of this deep weld in U-0.75 wt% Ti is shown in Fig. 4. Study of the tip of the weld at high magnification and with various etches and polishes indicated that there were no cold-shuts in this particular cross section. No other sections were made. Note the discontinuity in the heat-affected zone width at the step (Fig. 4, bottom photo) and the solidification patterns in the weld metal in the top photo. Both of these indicate the relatively low temperature of the weld root.

Figure 5 is a ×50 photomicrograph showing the structure of the heat-affected zone with new small grains in the center, the quenched structure of the plate at the right, and a small portion of the fused weld metal at the left.

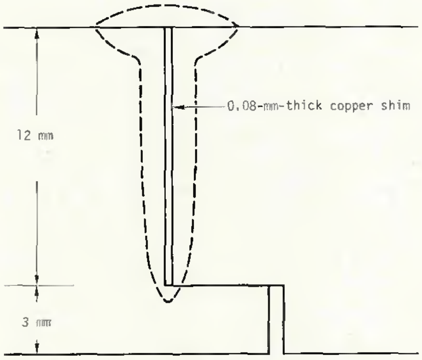

Fig. 3—Geometry of weld joint in U-0.75 wt% Ti plate welded with a copper shim

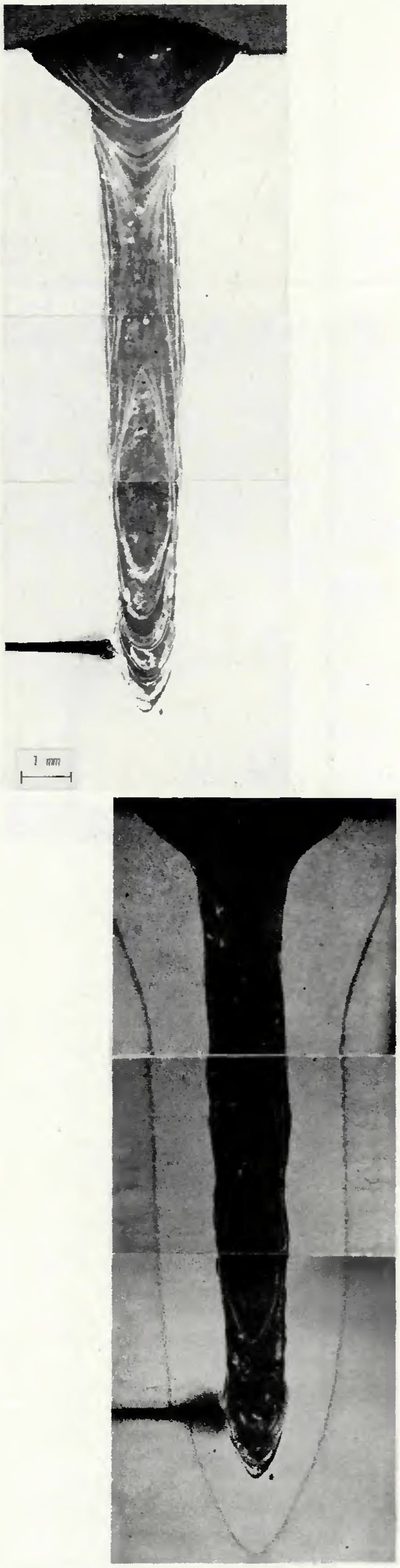

Fig. 4—Photomicrograph of weld shown in Fig. 3 made in U-0.75 wt% Ti. These two composite views are made from different exposure of the same negatives. Electrolytic etch with (8-5-5) plus air oxidation for 16 months

The fourth experiment investigated the use of 0.08 mm copper shims for electron beam welding of unalloyed uranium (D-38). Several 15.9 mm thick plates of D-38 were obtained from stock. We made no chemical analysis of this material, which had been rolled by Union Carbide Nuclear Company at the Y-12 plant, but carbon levels of about 200 ppm would be expected.

Two sets of plates were prepared by milling to a thickness of 12 mm, a length of 150 mm, and a width selected so that a welded pair was 70 mm wide. The weld joints were 9 mm deep to the step; the steps were 3 mm thick. The joints ran down the center of the specimens for the entire length. The first 50 mm of each joint had no shim. For the balance of the length of each joint, a 0.08 mm cut was made to accommodate a copper shim of that thickness.

The two joints were welded using the single-pass electron beam process. One of these weld joints, broken in an upright position using the step as an initiation point, is shown in Fig. 6. We were surprised by the difference in the fracture between the area without shim and that with shim. The area without the shim shows the familiar low-energy flat fracture characteristic of electron beam welded uranium. In the area with the shim, the fracture did not propagate through the weld metal, but rather went off at a slant of about 45 deg.

No cold-shuts were visible on the broken surface of the weld, either where there was copper or where there was not. Notice in Fig. 6 that the weld penetrated through the step to the underside of the plate, thereby burying cold-shuts deeper in the plate than previously. To observe whether there were cold-shuts in the root of this weld, we milled away this step to the centerline of the weld. The section was then polished with 3/0 paper and examined at ×25 with a binocular microscope. One observer counted 28, and another 30 cold-shuts in the 50

Fig. 5—A photomicrograph centered on the heat-affected zone of an electron beam weld made in U-0.75 wt% Ti plate using a 0.08 mm copper shim. Same etch as in Fig. 4

mm long region where there was no copper. No cold-shuts were found in the 100 mm region where there was copper. It would appear from this experiment that the copper shim is of considerable benefit.

The second welded D-38 plate was cut into tensile blanks. Four bars were cut across the "no shim" weld for controls, and six were cut across the copper-containing weld. These blanks were turned to form threaded tensile bars with a gage diameter of 4.064 mm and a gage length of 15.8 mm. Testing was done largely at two different crosshead speeds to give strain rates of 0.050 and 0.005 per min. The results shown in Table 2 indicate a slight increase in the strength of the welds due to the copper.

Examination with a scanning electron microscope of typical fracture surfaces and of polished sections perpendicular to the fractures did not reveal any apparent reason for the increased strength of the weld metal. The scanning electron microscope, equipped with an energy-dispersive unit, was not able to resolve areas that were copper-rich, nor could they be resolved in the optical microscope. The copper appeared to be quite finely distributed.

A fifth experiment was performed using a thorium shim in welding a plate of U-0.26 wt% V alloy. The face of this weld was much smoother than that of the copper-shim welds described above. There were, however, many more cold-shuts in this weld than in D-38 or U-0.26 wt% V alloy welded without a shim. It appeared that the thorium had caused a large change in viscosity, which negated any possible benefit due to melting-point change.

A final experiment involved a copper shim in a plate of U-0.26 wt% V alloy. This combination seemed to work quite well, and no cold-shuts were found. However, no cold-shuts were present in a control sample welded without any shim either. This experiment was, therefore, not conclusive, and more work will be necessary. The copper seemed to cause a much thinner, deeper penetration weld, and the root was fused well into a backing plate, while the vanadium alloy alone seemed to give a broader, less deep, fusion zone.

Table 3 gives across-the-weld tensile data. This U-0.26 wt% V alloy had the following impurities by weight: carbon, 21 ppm; aluminum, 600 ppm; silicon, 40 ppm; and hydrogen, 0.5 ppm. The plate had been beta quenched from 700 C (1292 F) after 4 h in vacuum, then recrystallized at 600 C (1112 F) for 3.5 h in vacuum to give a grain size of ASTM #5.

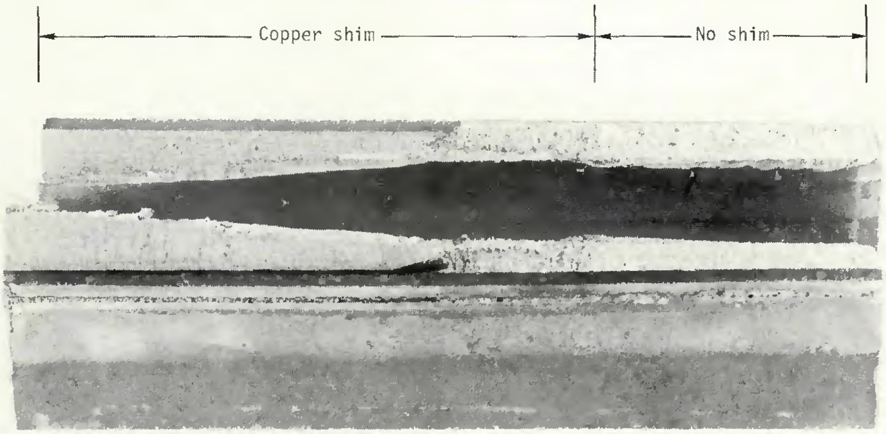

Fig. 6—Broken surfaces on an electron beam step-joint weld in a plate of D-38. The right hand portion had no shim, while the remainder contained a copper shim 0.08 mm thick. Note change in fracture path because of the shim

Literature Review

While the experimental program was in progress, an extensive literature survey was made. No publication was found that revealed work in which an alloy addition was made during welding for the purpose of eliminating cold-shuts.

Cold-shuts have been mentioned in Mileka's book on electron beam welding, where they are described as "necklace cracking." The only suggestion given for their elimination is "widening the weld, thus improving the ability of the metal to flow into the cavity."[5] In the same work, there is mention of a shim evidently used in the welding of Nimonic 115 alloy: "It is then beneficial to introduce a shim of Ni-Cr (80:20) material 0.01 in. (0.25 mm) thick, between the abutting joint faces before welding. The shim material has the effect of increasing the hot ductility of the weld metal, thus minimizing the tendency to cracking."[6] Here, of course, the cracking referred to is not the "necklace cracking" but rather true cracking under thermally induced stresses.

Another mention of shims used to eliminate hot cracking in high temperature alloys is in a work by King.[7] He states, "Sometimes a filler metal is used to create a more favorable metallurgy in the weld. As an example, 713 C vacuum-casting alloy [Inconel], when welded to itself, develops a condition that results in microcracking. However, the insertion of a strip of Udimet 500, of proper thickness, into the joint produces an apparently crack-free weld."

Table 2—Results of Across-the-Weld Tensile Testing of One Plate of D-38 Welded with and without a Copper Shim

	Specimen no.	Strain rate, min^{-1}	Tensile strength, MPa	0.2% yield strength, MPa	Elongation,(a) %	Fracture location(b)
Without copper	1827	0.005	652	292	9	W
	1828	0.050	667	299	6	W
	1829	0.005	660	273	11	W
	1830	0.500	616	290	5	W
With copper	1831	0.005	772	286	16	W
	1832	0.020	784	300	17	W
	1833	0.050	750	301	16	W
	1834	0.005	737	311	16	W
	1835	0.050	768	284	17	HAZ
	1836	0.050	742	297	13	W
	1837	0.005	783	299	19	HAZ

(a) Elongation over 16.4 mm gage length with a length-to-diameter ratio of 4, as determined by gage marks.
(b) Fracture Location: W = weld metal; HAZ = heat-affected zone.

Table 3—Room Temperature Tensile Properties of U-0.25 wt% V Tested at a Strain Rate of 0.01 min^{-1} (Average of Five Bars)

	Tensile strength, MPa	0.2% yield strength, MPa	Elong. in 4× bar diam, %	Red. in area, %	Fracture Location
Unwelded:					
transverse	983	410	11.2	12.4	
longitudinal	987	443	11.5	12.2	
Welded:	976	438	10.0	9.5	HAZ
Welded with 0.08 mm					
Cu shim:	976	448	10.4	8.4	HAZ[(a)]
	901	452	6.0	5.0	Weld[(b)]

(a) Average of four bars.
(b) These values are for a single bar as only one bar failed in the weld.

Turner and Lundin[8] have used foil, wire, and vapor deposits of iron to make controlled alloy additions of that material to welds in uranium, the objective being to study the adverse effects of that element in the hot cracking of weld metal without having to melt and fabricate a large number of alloys.

Arata, Matsuda, and Murakami[9] used nickel and stainless steel inserts in steel welds to study the dynamic aspects of the pool under the influence of the electron beam. They apparently assumed that the dynamics of the molten pool would not be altered by these additions.

In the Russian literature, two pertinent articles were found. Shiganov and Komarov[10] used shims of aluminum to help dilute the magnesium content of molten weld pools and thereby create "pore-free" joints. Veinik, Diyachenko, and Chukanov[11] used shims of vanadium to weld niobium alloy to stainless steel.

Shahinian, Atwell, and Brooks[12] used 1.6 and 3.2 mm diameter inserts of copper, nickel, and niobium wire in a one inch thick titanium plate to study the mixing in the electron beam welding process as a function of welding speed (457 to 508 mm/min) at 30 kV. They used a top surface focus and between 280 and 350 mA beam current.

Boncoeur, Heintz, Lavaud, and Rapin[13] have described a process they developed for use by the French Commissariat à l'Energie Atomique to determine whether or not an electron beam weld is penetrating to the desired depth in a uranium-vanadium alloy. This process uses a small copper wire embedded in the joint at the desired minimum penetration depth. The copper, if melted by the beam, contaminates the surface of the weld joint and also the vapors in the chamber just above the weld pool. Detectors are used either in the chamber during welding or on the surface after welding to determine if the weld penetration is adequate. They used 140 kV, 11 mA, and a welding speed of 22 or 25 mm/s on a Hamilton machine to give a penetration of 3 mm. This is not a deep penetration weld, and it would not therefore be susceptible to cold-shuts.

Conclusion

Copper shims eliminate cold-shut defects and provide small increases in the room temperature strength of welds in D-38. Copper shims also work well to eliminate cold-shuts in welding uranium low-vanadium and uranium low-titanium alloys. A thorium shim gave a bad weld with a uranium low-vanadium alloy.

We may have enough evidence to confirm the general hypothesis that lowering the freezing point of the weld pool by adding a shim of an appropriate metal in the weld joint will tend to eliminate cold-shut defects in deep, partial penetration, single-pass, electron beam welds. However, we recognize that there are other variables, such as viscosity and vapor pressure, to consider. Although our work has been with uranium alloys, we believe the basic concept is applicable to other metals and alloys.

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