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SELECTION OF FLOWING LIQUID LEAD TARGET
STRUCTURAL MATERIALS FOR ACCELERATOR
DRIVEN TRANSMUTATION APPLICATIONS

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Selection of Flowing Liquid Lead Target Structural Materials for Accelerator Driven Transmutation Applications

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Abstract. The beam entry window and container for a liquid lead spallation target will be exposed to high fluxes of protons and neutrons that are both higher in magnitude and energy than have been experienced in proton accelerators and fission reactors, as well as in a corrosive environment. The structural material of the target should have a good compatibility with liquid lead, a sufficient mechanical strength at elevated temperatures, a good performance under an intense irradiation environment, and a low neutron absorption cross section; these factors have been used to rank the applicability of a wide range of materials for structural containment. Nb-1Zr has been selected for use as the structural container for the LANL ABC/ATW molten lead target. Corrosion and mass transfer behavior for various candidate structural materials in liquid lead are reviewed, together with the beneficial effects of inhibitors and various coatings to protect substrate against liquid lead corrosion. Mechanical properties of some candidate materials at elevated temperatures and the property changes resulting from 800 MeV proton irradiation are also reviewed.

INTRODUCTION

Flowing liquid lead is the primary candidate target material for use as the compact, high-power spallation neutron source for the accelerator based conversion of plutonium/accelerator transmutation of waste (ABC/ATW) system at Los Alamos National Laboratory (LANL). The liquid lead target appears to be the best possible choice with its unique advantages including: high atomic number ($Z = 82$), moderate melting point (327°C), fast heat removal from the target, good neutron yield, low vapor pressure, and no worry about radiation damage to the target material. Lead was chosen over lead-bismuth eutectic because of the following undesirable properties of lead-bismuth eutectic. (1) Lead-bismuth eutectic produces α -radioactive ^{210}Po by capture of thermal neutrons in bismuth. (2) Lead-bismuth eutectic is more corrosive than lead, for example, the corrosion of steel in uninhibited bismuth is about 40 times greater than it is in uninhibited lead under similar conditions [1]. Materials known to be compatible with lead-bismuth have a high thermal neutron absorption cross section; preferred materials such as aluminum or zirconium are not considered compatible. (3) Lead-bismuth eutectic has unfavorable behavior of retained swelling after solidification. A simple test to measure this effect was conducted [2]. A 6.55-cm O.D. cylinder constructed from 0.175-cm thick chrome-steel was filled with molten Pb-Bi and then allowed to solidify. The diameter increased by a maximum of 0.35% over a period of 6 months with no measurable change of diameter at later times. The consequence of this test suggests that solidification of Pb-Bi may require additional structure beyond that required for mere fluid containment.

In the current preconceptual target design, liquid lead is circulated ($400\text{--}500^{\circ}\text{C}$) through an active spallation region where it picks up sensible heat that is later transferred to a secondary coolant. This design is unique in that the beam window is an integral part of the target containment structure and is convectively cooled by the flowing lead. Consequently, the structural container for the molten lead will be exposed to a significant flux of high-energy protons and neutrons as well as an extremely corrosive environment. Selection of the container material will greatly affect the lifetime and safety of the target subsystem; the material should have good compatibility with molten lead, sufficient mechanical strength at operating temperatures, a low neutron absorption cross section, and good performance under an intense radiation environment. In this paper, an effort to

summarize the down-selection process that led to the selection of Nb-1Zr as the leading container material is made.

In selecting a structural material for use in any liquid metal application, a number of important factors must be considered including compatibility of the structural material with the liquid metal, the application's thermal and radiation environments, and the physical geometry of the container. In ABC/ATW system, operational conditions are very similar to those encountered in nuclear reactor system. The exception to this general analogy is in the spallation target region where a high-energy proton and neutron flux exists. Consequently, the large corporate knowledge base of liquid metal reactor systems is applicable, but not conclusive. For the particular application of a circulating molten lead spallation target, three factors have been used to rank the applicability of a wide range of materials for structural containment: good compatibility with liquid lead, sufficient mechanical strength under elevated temperature and intense irradiation, and good neutron yield.

MATERIALS COMPATIBILITY WITH LIQUID LEAD

One of the major factors limiting the design and lifetime of most elevated temperature liquid metal engineering systems is liquid metal corrosion. In contrast to aqueous corrosion, electrochemical reactions are generally not involved in liquid metal corrosion; however, chemical reactions combined with physical phenomena can occur readily in liquid-metal systems. Liquid metal corrosion tests are performed statically and dynamically. A static corrosion test simply involves the interaction of a solid metal specimen with a liquid metal for a suitable length of time at a desired temperature. A dynamic corrosion test usually employs circulation of the liquid through a temperature gradient to account for the mass transfer of the container material [3-5].

There are a number of different types of liquid metal corrosion: dissolution attack, temperature gradient mass transfer, concentration gradient mass transfer, impurity reactions, erosion, intergranular attack, alloying between the liquid metal and the solid containment metal, self-welding of solid metals, and liquid metal embrittlement. Of all the above mechanisms, temperature gradient mass transfer is usually the most damaging type in applications where there is a large temperature gradient in the system. The solubility of the container material in the liquid metal is a function of temperature. After a period of operation, solubility limits are reached and the temperature dependent solubility results in the transfer of the container material from the hottest location to the coldest location in the flowing loop. The effect in the circulating molten lead target is to dissolve container material from the window and deposit it in the heat exchanger. Both the thinning of the window and potential fouling of the heat exchanger are undesirable.

The relative resistance to mass transfer in liquid lead of 24 metals and alloys with a temperature gradient of 300°C (800-500°C) was measured by Cathcart and Manly [6], and the results are shown in Table 1. The materials tested were divided into three groups based on their relative resistance to mass transfer in a thermal convection loop test. The "heavy mass transfer" group included nickel, titanium, cobalt, chromium, iron, beryllium, Inconel, 304 stainless steel, and 310 stainless steel. The "usually little mass transfer" group included Hastelloy B, 410 stainless steel, 446 stainless steel, Fe-14Cr-2Si, Ni-25Mo, Co-45Cr, Fe-50Mo, Fe-37Cr-16Ni, and Fe-50Cr. Finally, the "no mass transfer" group included niobium and molybdenum. In an ORNL thermal convection loop test, Croloy 2-1/4 (Fe-2.25Cr-1Mo) exhibited 1-8 mils of attack at 593-654°C, and Nb-1Zr showed no attack after 5280 hrs exposure to lead at 760°C [7]. In another thermal convection loop test [8], chromium and austenitic steel showed 42-320 µm attack at 600 °C for 1000-2000 hrs; however, Nb, Nb-1Zr, Nb-5V, and V showed no attack at 625°C for 1858 hrs. The tests also showed that the corrosion attack was strongly increased due to stresses in material; the depth of corrosion attack was much higher in the bent region of U-shaped specimens than in the rest of the specimens. In conjunction with the LMFR program, BNL also ran a Croloy

2-1/4 loop containing 225 ppm Mg-inhibited (used as a deoxidant) lead for over 27,765 hrs with a temperature differential of 105°C (550–445°C); no significant corrosion was observed [9]. A thermal convection loop test with a maximum hot-zone temperature of 550°C and a minimum cold-zone temperature of 470°C was performed on ferritic steels of Chromesco 3 (2-1/4 Cr) and EM 12 (10 Cr) [10,11]. The result showed that in the hot zone, the thickness loss of Chromesco 3 steel was about 90 µm, whereas, that of EM 12 was only 30 µm. In the cold zone, an abundant deposit of iron crystals up to several millimeters thick was formed on Chromesco 3 steel. On the other hand, a much thinner deposit of 0–35 µm of iron and magnetite was formed on EM 12. Asher et al. [12] have shown that, in their loops at 700°C with $\Delta T = 150^\circ\text{C}$, Hastelloy N was severely attacked in only 4 days, and Croloy 2-1/4 was severely attacked in 15 days; however, molybdenum showed no attack in 282 days.

Dissolution attack is another important consideration for liquid metal corrosion. From the results of a static corrosion test, the evaluation of materials according to their resistance to attack by liquid lead has been studied [13,14], and is summarized in Table 1. At 600°C, the materials with good resistance included niobium, molybdenum, tantalum, tungsten, beryllium, iron, mild carbon steel, low chromium steel, and ferritic stainless steels. Aluminum, titanium, and zirconium exhibited limited resistance. Austenitic stainless steels, copper-base alloys, nickel, and nickel-base alloys showed poor resistance. In another static corrosion test of steels [10,11], austenitic steel (15Cr-15Ni) showed a strong attack with deep intergranular attack (up to 150 µm) at 530–600°C for 3000 hrs, whereas, ferritic steels (Chromesco 3 and EM 12) showed slight attack with no intergranular attack at 430–575°C for 1100–2100 hrs.

The loss of ductility and fracture strength experienced by a metal when stressed in tension while in contact with liquid metal is known as liquid metal embrittlement (LME). LME experiments with AISI 4145 steel showed that both fracture strength and ductility decreased in a continuous manner at temperatures considerably below the melting point of lead, and reached a minimum just above the melting point, and then increased rapidly [15]. Experiments with AISI 3340 steel showed loss of ductility in the temperature range of 315–427°C [16]. Chromesco 3 steel showed a slight decrease in the reduction of area (10%) and ultimate tensile strength in the temperature range between 327 and 350°C [10]. All of above data show that the ductility drop in steel is significant near the melting point of lead.

It has been found that the addition of 50–500 ppm of zirconium and titanium to liquid mercury and bismuth inhibits solution mass transfer of steels by reacting with nitrogen and carbon from the steel to form inert, adherent surface layers of ZrN, TiN or TiN + TiC [17]. As with bismuth and mercury, the corrosion of steels in lead was reduced significantly by the addition of 500 ppm of titanium. James and Trotman [1] reported that liquid lead containing 500 ppm titanium in combination with the low alloy steel with available nitrogen or carbon was the most corrosion resistant system among 0.3% carbon steel, mild steel, CRM-6, Fe-13Cr, and 18-8 stainless steel [1]. Asher et al [12] also showed that Croloy 2-1/4, although severely attacked in uninhibited lead for 4 days, did not show any attack in Ti-inhibited lead for 85 days.

The two effects of oxygen in lead have been discussed by Weeks [18]. Oxygen can form oxide layers on the surface of steels, especially those high in chromium, which reduce the corrosion rate. The lead oxide (PbO) is less stable than oxides of Fe and Cr, and is slightly soluble in liquid lead. Thus, there is a tendency for Pb to reduce Fe or Cr oxides in the hot leg of a loop and transfer oxygen to the minimum temperature of the system, where PbO precipitates from the solution and might form a plug. For these reasons, oxide films on a steel are only temporarily beneficial to its corrosion behavior, and could result in oxide plugs in the cold leg of the circuit. It appears that, from the result of BNL loop test, neutron irradiation does not increase corrosion or reduce the effectiveness of inhibitor [19].

Table 1. Properties of Selected Materials

Material	Density (g/cm ³)	T _m (°C)	ACS (barns)	Mass transfer	Resistance to attack	UTS (MPa)	UTS(500) (MPa)	YS(500) (MPa)
Be	1.85	1283	0.009	heavy	good	228-690	145-170	
Mg	1.74	650	0.063			90-220		
Al	2.70	660	0.215			40-140		
Ti	4.51	1668	5.6	heavy	limited	220	100	
V	6.09	1735	5.1			472-911		
Cr	7.19	1890	2.9	heavy		413	225-242	
Mn	7.44	1245	13.2		poor	496		
Fe	7.87	1539	2.53	heavy	good			
Co	8.89	1495	37	heavy		234-945		
Ni	8.91	1455	4.6	heavy	poor	317		
Cu	8.92	1083	3.69		poor	209-344		
Zr	6.51	1845	0.18		limited			
Nb	8.57	2415	1.1	no	good	210-334	200-290	90-120
Mo	10.22	2610	2.5	no	good	400-600	250-350	
Ru	12.48	2334	2.46					
Rh	12.44	1966	150			951-2068		
Hf	13.09	2222	115					
Ta	16.68	2996	21.3		good	250-400	200-300	
W	19.26	3410	19.2		good	560-3922	196-1667	
Re	21.03	3170	84			990-2400	1250	
Os	22.6	2700	14.7					
Ir	22.5	2454	430			990-2480	530	
Pt	21.45	1769	8.1		poor			
Th	11.66	1750	7			150-250	50-80	
304 ss	7.9	1425		heavy	poor	515-2240		
304L ss	7.9	1425			poor	480-620		
310 ss	7.9	1425		heavy				190
316 ss	8.0	1390			poor	515-1690		
316L ss	8.0	1390			poor	480-620		
347 ss	8.0	1412		heavy				
410 ss	7.7	1505		little		485-825	450	380
446 ss	7.6	1467		little			280	
Inconel	8.5	1410		heavy		697	650	
Inconel 718	8.19					995-1448	990-1200	
Hastelloy B	9.24	1335		little		583	531	
Hastelloy N	8.93					724	586	
Zircaloy-2	6.5	1817	0.193			570		
Zircaloy-4	6.5	1817	0.194					
Nb-1Zr	8.4	2467				280	200	130
PWC-11	8.4	2467				345	262	150
T-111	16.7	2977				690	379	
Mo-13Re	10.9	2537				550	530	
TZM	10.2	2610				552-883		
Croloy 2-1/4	7.9	1530				680	470	220
HT-9	7.7	1520					550-1500	500-1100

Density = density at 25°C in g/cm³

T_m = melting point in °C

ACS = absorption cross section for 2200 m/s neutrons in barns/atom

Mass transfer = mass transfer in liquid lead from J. V. Cathcart and W. D. Manly

Resistance to attack = resistance to attack by liquid lead at 600°C from *Liquid Metals Handbook*

(good = rate of attack is less than 1 mil/year, limited = rate of attack is 1 to 10 mils/year,

poor = rate of attack is greater than 10 mils/year)

UTS = ultimate tensile strength at room temperature

UTS(500) = ultimate tensile strength at 500°C

YS(500) = 0.2% yield strength at 500°C

304 ss = Fe-(18-20)Cr-(8-12)Ni-2Mn-1Si-0.08C-0.045P-0.03S

304L ss = Fe-(18-20)Cr-(8-12)Ni-2Mn-1Si-0.03C-0.045P-0.03S

310 ss = Fe-(24-26)Cr-(19-22)Ni-2Mn-1.5Si-0.25C-0.045P-0.03S

316 ss = Fe-(16-18)Cr-(10-14)Ni-2Mn-1Si-0.08C-0.045P-0.03S-(2-3)Mo

316L ss = Fe-(16-18)Cr-(10-14)Ni-2Mn-1Si-0.03C-0.045P-0.03S-(2-3)Mo

347 ss = Fe-(17-19)Cr-(9-13)Ni-2Mn-1Si-0.08C-0.045P-0.03S-10 x % C min Nb + Ta

410 ss = Fe-(11.5-13)Cr-1Mn-1Si-0.15C-0.04P-0.03S

446 ss = Fe-(23-27)Cr-1.5Mn-1Si-0.2C-0.04P-0.03S

Inconel = 72Ni-15.5Cr-8Fe-1Mn-0.5Si-0.15C

Inconel 718 = 52.5Ni-19Cr-18Fe-5.2Nb-3.0Mo-1.0Co

Hastelloy B = 67Ni-28Mo-5Fe

Hastelloy N = 68Ni-17Mo-7Cr-5Fe

Zircaloy-2 = Zr-1.5Sn-0.14Fe-0.1Cr-0.06Ni

Zircaloy-3 = Zr-0.25Sn-0.25Fe-0.05Cr-0.05Ni

Zircaloy-4 = Zr-1.5Sn-0.17Fe-0.12Cr

T-111 = Ta-8W-2Hf

PWC-11 = Nb-1Zr-0.06C

TZM = Mo-0.5Ti-0.1Zr

Croloy 2-1/4 = Fe-2.25Cr-1Mo-0.15C

HT-9 = Fe-12Cr-1Mo-0.5Ni-0.5W-0.3V-0.2C

The use of coatings to protect substrate against lead corrosion has not been successful because of thermal expansion mismatch, with the exception of plasma sprayed molybdenum coating on Croloy and aluminized specimen of the same steel [12]. In the former case, the protection was attributed to the high corrosion resistance of molybdenum, and in the latter case, it was probably by the formation of protective oxide films.

MECHANICAL STRENGTH OF MATERIALS

A sufficient mechanical strength at service temperatures is also very important in the selection of structural materials for the circulating molten lead target. Preliminary design inlet and outlet temperatures of the flowing lead are 400 and 500°C, respectively. The mechanical properties of selected candidate materials are shown in Table 1. Note, however, that the strength of a material depends on many factors, primarily processing history and impurity levels; the mechanical strengths shown in Table 1 should not be regarded as absolute. In the preliminary target design, the maximum hoop stress in the container has been calculated to be approximately 28 MPa at a lower temperature region (400°C). At this high stress location, aluminum-base alloys will lose most of their strength because of their low melting point (around 660°C). As shown in Table 1, other common structural materials such as stainless steels, nickel-base alloys, zirconium-base alloys, refractory alloys, and iron-base heat resistance alloys (for example Croloy 2-1/4 and HT-9) will have enough strength at this location.

More importantly is the strength of the material at the highest temperature location. In the current design, it is estimated that the maximum temperature of the system will be approximately 900–1000°C at the point where the proton beam impinges on the window. At this temperature range, iron-base alloys are inadequate because they have melting points of 1400–1500°C and creep becomes significant problem at above half of the melting point of the material. Iron-base alloys are usually limited up to 650–700°C. Similarly, nickel-base and cobalt-base superalloys are marginally acceptable because they are limited up to 900–1000°C. Another consideration for the use of these superalloys is that nickel is incompatible with liquid lead, and cobalt has very high absorption cross section (37 barns). Refractory metals (Nb, Ta, Mo, W) are usually considered at service temperatures above 900°C.

Mechanical property change of materials upon intense proton irradiation is another factor to be considered. Samples of Fe, Ta, Fe-2.25Cr, and Fe-12Cr-1Mo were sealed inside capsules containing Pb-Bi, and were irradiated by 800 MeV proton beam by Brown et al. [20]. Room temperature tensile tests on these samples indicated that the strength increases and ductility decreases, which is consistent with the well-known effects of fission-neutron irradiation. Based upon the measured ductility and strength, it appeared that the two iron base alloys would be suitable for a proton beam window in contact with Pb-Bi as long as the window temperature does not exceed approximately 673 K. They have also performed mechanical tests of 304 stainless steels, alloy 718, molybdenum, and tantalum after low fluence 800 MeV proton irradiation in a separate experiment [21]. For 304 stainless steel and alloy 718, the ductility decreased approximately 30–40%. Tantalum still retained significant ductility, while several molybdenum specimens broke at less than 0.2% strain.

NEUTRON ABSORPTION CROSS SECTION

The candidate structural material should also have a low thermal neutron absorption cross section to offer maximum neutron yield. The neutron absorption cross section of selected materials are also included in Table 1. Beryllium has the lowest absorption cross section (0.009 barns); however, it exhibited heavy mass transfer in liquid lead [6]. Aluminum has a good absorption cross section (0.215 barns); however, it has a low melting point of 660°C. Zirconium has a good absorption cross section (0.18 barns), as does niobium (1.1 barns), iron (2.53 barns), and molybdenum (2.5 barns). Tantalum (21.3 barns), rhenium (84 barns), and tungsten (19.2 barns) have relatively high absorption cross sections.

SUMMARY

Nb-1Zr has been selected for use as the structural container for the LANL ABC/ATW molten lead target. It has been shown to be compatible with molten lead, it has sufficient mechanical strength at operating temperatures near 1000°C, and it has a low neutron absorption cross section. Because of these same attributes, Nb-1Zr was chosen as the primary structural material for the SP-100 space nuclear power system. It is readily available in all product forms from several commercial sources, and has a significant data base for fission irradiated performance. Molybdenum has a little higher mechanical strength and neutron absorption cross section than niobium, and has good compatibility with liquid lead. However, its brittle behavior following even a short-term irradiation of protons make it unattractive. Although ferritic steels showed significant resistance to mass transfer in liquid lead, their low strength at 1000°C make them unattractive as a window material. Ferritic steels are more corrosion resistant than austenitic steels, consequently, ferritic steels could be used with Mg- or Ti-inhibitor in lower temperature region of the system. Zirconium has some attractive properties such as a very low neutron absorption cross section and relatively high melting point (1845°C); however, its mass transfer behavior in liquid

lead is not known. Beryllium has very good absorption cross section, but it exhibited heavy mass transfer. Nickel and nickel base alloys have a very low resistance to mass transfer in liquid lead.

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REFERENCES

- [1] James, J. A., and Trotman, J., "Corrosion of Steels in Liquid Bismuth and Lead," *J. Iron and Steel Inst.* **194**, 319-323 (March 1960).
- [2] Dubs, M., and Ulrich, J., "Design Considerations for the SING Target Window," in *Proceedings of the 11th Meeting of the International Collaboration on Advanced Neutron Sources (ICANS-XI)* (1990).
- [3] Cathcart, J. V., and Manly, W. D., "A technique for Corrosion Testing in Liquid Lead," *Corrosion* **10**, n.12, 432-434 (1954).
- [4] Epstein, L. F., "Corrosion by Liquid Metals," in *Proceedings of International Conference on the Peaceful Uses of Atomic Energy*, 1955, pp. 311-317.
- [5] Manly, W. D., "Fundamentals of Liquid Metal Corrosion," *Corrosion* **12**, 336t-342t (1956).
- [6] J. V. Cathcart and W. D. Manly, "The Mass Transfer Properties of Various Metals and Alloys in Liquid Lead," *Corrosion* **12**, 43-47 (1956).
- [7] G. M. Tolson and A. Taboada, "A Study of Lead and Lead-Salt Corrosion in Thermal-Convection Loops," Oak Ridge National Laboratory report ORNL-TM-1437 (1966).
- [8] I. Ali-Khan, "Corrosion of Steels and Refractory Metals in Liquid Lead," *Materials Behavior and Physical Chemistry in Liquid Metal Systems*, 1982, pp. 243-252.
- [9] Romano, A. J., Klamut, C. J., and Gurinsky, D. H., "The Investigation of Container Materials for Bi and Pb Alloys: Part I. Thermal Convection Loops," Brookhaven National Laboratory report BNL 811 (July 1963).
- [10] Broc, M., Sannier, J., and Santarini, G., "Experimental Studies on the Use of Liquid Lead in a Molten Salt Nuclear reactor," *Nuclear Technology* **63**, 197-208 (1983).
- [11] Broc, M., Sannier, J., and Santarini, G., "Behavior of Ferritic Steels in the Presence of Flowing Purified Liquid Lead," *Liquid Metal Engineering and Technology*, London, 1984, vol. 1, pp. 361-368.
- [12] Asher, R. C., Davies, D., and Beetham, S. A., "Some Observations on the Compatibility of Structural Materials with Molten Lead," *Corrosion Science* **17**, 545-557 (1977).
- [13] R. N. Lyon (ed.), "Liquid Metals Handbook," Atomic Energy Commission, Department of the Navy, Washington, D. C., NAVEXOS P-733 (Rev.) (June 1952).
- [14] Wilkinson, W. D., Hoyt, E. W., Rhude, H. V., "Attack on Materials by Liquid Lead," Argonne National Laboratory report ANL-5449 (October 1955).
- [15] Breyer, N. N., and Johnson, K. L., "Liquid Metal Embrittlement of 4145 Steel by Lead-Tin and Lead-Antimony Alloys," *J. Testing and Evaluation* **2**, 471-477 (1974).
- [16] Dinda, S., and Warke, W. R., "The Effect of Grain Boundary Segregation on Liquid Metal Induced Embrittlement of Steel," *Materials Science and Engineering* **24**, 199-208 (1976).
- [17] Kammerer, O. F., "Zirconium and Titanium Inhibit Corrosion and Mass Transfer of Steels by Liquid Heavy Metals," *Trans. of the TMS of AIME*, 20-25 (Feb. 1958).
- [18] Weeks, J. R., "Lead, Bismuth, Tin and Their Alloys as Nuclear Coolants," *Nuclear Engineering and Design* **15**, 363-372 (1971).
- [19] Waide, C. H. et al., "Uranium-Bismuth In-Pile Corrosion Test Loop," Brookhaven National Laboratory report BNL -736 (1961).
- [20] Brown, R. D., Wechsler, M. S., Tschalaer, C., "Tensile Properties of Several 800 MeV Proton-Irradiated BCC Metals and Alloys," in *Effects of Radiation on Material Properties: 13th International Symposium (Part II, ASTM STP-956)*, 1987, pp. 131-140.
- [21] Brown, R. D., and Cost, J. R., "Mechanical Properties of 800-MeV Proton-Irradiated Metals," *Effects of Radiation on Materials (ASTM STP 782)*, 1982, pp. 917-926.

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