Despite the fact that the compacts were vibrated during loading the maximum apparent densities achieved were 2.04 g/cc or 46 percent of theoretical density based on 4.43 g/cc.

Two billets were compacted at fluid pressures of 60,000 psi and the remaining three billets were compacted at fluid pressures of 225,000 psi. Each compact was held at pressure for between 10 and 15 seconds before the maximum pressure was slowly released. To compensate for shrinkage during compaction and the consequent lowering of fluid level in the container, the three billets pressed at 225,000 psi were compacted at two intermediate pressures, 15,000 and 65,000 psi. On attaining these pressures, the pressure was removed and fluid added, but the compacts were not disturbed.

The compacted billets were sintered at 2200 F for 1 hour in an argon atmosphere and water quenched. One of the billets pressed at 60,000 psi broke up upon quenching. The water densities of the billets before and after sintering are given below:

Compacting Pressure, psi	Water Density, percent of theoretical density	
	Before Sintering	After Sintering
60,000	93.4	93.2
225,000	97.5	97.5

The sintered compacts are to be machined into billets and extruded into rods under conditions that have been successful for extruding wrought Ti-6Al-4V. The resulting extrusions will then be evaluated and compared to the wrought material extrusions from the standpoint of surface finish and mechanical properties.

HYDROSTATIC EXTRUSION OF WROUGHT TZM MOLYBDENUM ALLOY AND BERYLLIUM ROUNDS

Efforts were continued in the study of die design with the aim of preventing cracking of relatively brittle materials during hydrostatic extrusion without the necessity of a fluid counter-pressure system. In the previous Interim Report VIII[6], two basic die concepts were explored: the controlled taper-relief and double-reduction die designs. These are illustrated in Figure 3 along with the standard die profile. The controlled-relief die was designed to effect a gradual release of the elastic stresses present in the extrusion on exit from the die land. This was found to be effective in reducing the number of circumferential or transverse cracks that occurred in hydrostatic extrusion of TZM and beryllium, although longitudinal hairline cracking still persisted.

The double-reduction die was designed to take a very small reduction of the product at a second land shortly beyond the first. It was believed that the second reduction, in addition to preventing transverse cracks by imposing a longitudinal compressive stress, could prevent longitudinal cracking by effecting a favorable change in the residual stress pattern. Specifically, a favorable change would be in the direction of reducing the level of residual hoop tensile stresses in the product which give rise to longitudinal cracking. The degree of change in the pattern would appear to depend on extrusion conditions including the size of the first and second reductions, the distance between lands, the relief configuration after each land, billet material, die angle, extrusion speed, and extrusion temperature.

Several double-reduction die designs have been investigated thus far:

Double-Reduction Die Designation	Second Reduction, percent	Distance Between Lands, H, inch[a]	Included Angle of Second Reduction, θ degrees[a]	Total Reduction, percent
A	1.5	5/8	45	60
B	3.3	5/8	45	75
C	2.0	5/8	45	74.6
D	2.0	0	45	74.6

(a) See Figure 3 for details

The experimental data obtained with these dies are contained in Table 4.

The results obtained with these dies are truly significant. For the first time, beryllium has been cold hydrostatically extruded at a ratio of 4:1 into virtually a crack-free product without the need of fluid back pressure (Trial 495). Similarly, wrought TZM alloy, in both the stress-relieved and recrystallized states, was extruded into crack-free products at a ratio of 4:1. This represents a major breakthrough of utmost importance in deformation of brittle materials.

In the previous interim period[6], only Die Design A had been evaluated on TZM (Trial 469). Transverse cracks were eliminated but longitudinal hairline cracking still occurred. Increasing the second reduction from 1.5 to 3.3 percent (Design B), and the overall extrusion ratio from 2.5 to 4:1 while maintaining the 5/8-inch spacing between lands, permitted the extrusion of a 1-inch length of crack-free product (Trial 478). Only a short extrusion was produced because runout pressures rose rapidly indicating lubrication breakdown and the trial was stopped. The reason for the pressure rise was not clear, but it was felt that a smaller second reduction might improve runout conditions.

In Die C, the reduction in area at the second bearing was reduced to 2.0 percent, the overall reduction remaining nominally 75 percent. This modification was effective in preventing cracks in both recrystallized TZM (Trial 483) and beryllium (Trial 495). Figure 4 shows the crack-free TZM extrusion along with two other extrusions obtained earlier with the standard die profile. The fact that cracking occurred at a higher extrusion ratio (5:1 in Trial 443 versus 4:1 in Trial 483) with the standard die indicates that:

(1) Merely increasing the extrusion ratio and using a standard die profile may not necessarily prevent cracking as suggested by Pugh.[8]

(2) Die design itself is a very important factor in controlling the conditions which cause cracking.

The surface finish of crack-free TZM extrusion was excellent (30 to 45 microinches, rms), even though the PTFE lubricant was apparently scraped off at the second bearing.