$k_2 = 2.0$. The other effects are coupled; reducing the outside diameter while maintaining the design pressure increases the interference required, but limiting the interference causes a reduction in maximum pressure because the interference depends upon the pressure.

Residual Stress Limitations

A container designed for a specific cyclic pressure requires certain residual stresses (prestresses) at operating temperature. It is also important, however, to check the residual stresses at room temperature because of differences in thermal expansion.

Calculations of residual stresses are given here for the multi-ring container as an example. (Residual stresses and operating stresses are given for all containers in Appendix C where computer programs are also listed. The specific container design discussed here is the one considered in the foregoing section for a bore diameter of 6 inches. Calculations are performed for design applications at room temperature, 500 F, and 1000 F. The material data assumed are given in Table 11. The liner material is assumed to be 18 percent Ni maraging steel, and the outer cylinders are assumed to be made of modified H-11 steel. The differences in thermal expansion for these materials are likely to be the largest expected among the steels that may be used.

TABLE 11. ELEVATED-TEMPERATURE DATA FOR 18% Ni MARAGING STEEL AND H-11 STEEL[(a)]

	70 F	500 F	1000 F
	Modulus of Elasticity, psi		
18% Ni Maraging	26.5×10^6	23.0×10^6	18.7×10^6
H-11	30.0×10^6	27.4×10^6	22.8×10^6
	Coefficient of Thermal Expansion, in./in./F		
18% Ni Maraging	5.6×10^{-6}	5.6×10^{-6}	5.6×10^{-6}
H-11	7.12×10^{-6}	7.25×10^{-6}	7.37×10^{-6}

(a) Poisson's ratio taken as constant, $\nu = 0.3$ for both materials.

Results are given in Table 12. The range and mean stress parameters were $\alpha_r = 0.5$ and $\alpha_m = 0.5$, respectively. The results show that the excessive residual stresses at room temperature occur for the multi-ring container having a required prestress, $\sigma_\theta = -\sigma_1$ at 500 F and 1000 F; i.e., the residual stress $\sigma_\theta < -\sigma_1$ at room temperature, where σ_1 is the design stress and $\sigma_1 \leqq$ ultimate tensile strength. The reason for this is the larger interferences required for elevated-temperature application as shown in Table 12. Larger interferences are necessary for high-temperature applications because the outer rings expand more than the liner due to the differences in thermal expansions as shown in Table 7. On the other hand, reduction of the temperature from operating temperature to room temperature causes the outer rings to tend to contract more than the liner. The liner resists the contraction and the residual interface pressures are increased, thereby increasing the magnitude of the residual hoop stress at the bore.

If the multi-ring container is to be used at 500 F and 1000 F with the material properties given in Table 11, then the prestress requirement, $\sigma_\theta = -\sigma_1$ at temperature ($\alpha_m = -0.5$) has to be relaxed. Accordingly, calculations of residual stresses and interferences are rerun for $\alpha_m = -0.3$ (prestress $\sigma_\theta = -0.8\ \sigma_1$ at temperature). These results are shown in Table 9. With $\alpha_m = -0.3$, excessive residual stresses at room temperature are avoided for the 500 F design. However, for operation at 1000 F, $\alpha_m >$ -0.3 is necessary since $\sigma_\theta < -\sigma_1$ at room temperature for the 1000 F design with $\alpha_m =$ -0.3.

Decreasing the interference fit (from those in Table 12 to those in Table 13), in order to avoid excessive residual stresses at room temperature, increases $(\sigma_\theta)_{max}$ from 0 to positive values. As pointed out in the latter part of the Fatigue Criteria section, zero to small $(\sigma_\theta)_{max}$ is expected to be beneficial in preventing the detrimental effect of fluid pressure from entering voids in the material. Therefore, if excessive residual stresses are to be avoided in containers designed for high temperatures, and if $(\sigma_\theta)_{max}$ is to be kept small, then the thermal coefficients of expansion of the component parts of the container should be more closely matched than those of Table 11. Preferably the coefficient of thermal expansion should be larger for the liner than for the outer cylinders; this would cause a reduction rather than an increase in residual stresses upon decreasing the temperature from operating temperature to room temperature.

Other Possible Material Limitations

It has been postulated that a maximum-tensile-stress fatigue criterion applies to the high-strength liner. Accordingly, fatigue data from uniaxial tension and rotating-beam bending tests were used to evaluate fatigue behavior of liners for high-pressure containers. However, the state of stress in an open-end hydrostatic extrusion container is biaxial and in a closed-end container a triaxial state of stress exists. (A triaxial state of stress may also occur in a shrink-fit open-end container where axial stresses may be produced by interface friction between shrink-fitted rings.) The effect of combined stresses on the fatigue strength of high-strength steels is unknown. It is pointed out, however, that the analyses performed in this study allow for arbitrary material behavior; i.e., the fatigue parameters α_r and α_m used in tha analysis are left arbitrary in the equations and could be determined from combined-stress fatigue experiments.

It has also been postulated that a compressive mean stress may benefit material fatigue strength under cyclic fluid pressure. However, biaxial and triaxial fatigue behavior under compressive mean stress is unknown. Even fatigue data in the uniaxial case are lacking for conditions of compressive mean stress.

Also unknown is the possible fracture of high-strength steels under large compressive stresses. Pugh and Green[21] and Crossland and Dearden[22] found for cast iron that the fracture strain and ductility (and the maximum shear stress at fracture) are increased by superimposing hydrostatic pressure. Bridgman[23] found similiar but less conclusive results for steel. These are favorable results for the effect of true hydrostatic pressure, but the possibility of similiar behavior when only one principal stress (the radial stress in a container) is highly compressive is unknown and should be