CREEP CHARACTERISTICS OF LEAD AND LEAD ALLOYS FOR USE IN THE ACCELERATOR PRODUCTION OF TRITIUM (APT) TARGET/BLANKET

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EXECUTIVE SUMMARY

We investigated the creep resistance of lead and lead alloys to address long-term effects for possible use in the Accelerator Production of Tritium (APT) target/blanket (T/B) design. A literature survey was performed to collect all available creep data on pure lead and other lead alloys. The survey produced numerous potential candidate alloys with respect to the material chemical composition. The APT physics team assisted in determining the neutronics characteristic, which eventually determined the type and amount of alloying element that is impregnated in pure lead. As such, a small subset of the candidate leads and alloys were evaluated to determine the overall creep characteristics based on operating conditions of the APT.

Much of the creep data collected pertains to low-temperature conditions [between 20 and 65.5°C (68 and 150°F)]. Lead and some lead alloys have a melting temperature of 327°C (620°F), and creep effects generally are very pronounced at ~0.4T_M (or 40% of the absolute melting temperature). Thus, at APT operating conditions of 104°C (219.2°F), there would exist a large amount of creep straining. However, alloying of pure lead increases the creep resistance dramatically, depending on the type and amount of alloy.

Preliminary results of creep strain-rate characteristics for lead and lead alloys, based on extrapolation of low-temperature data to an elevated temperature, show that none of the possible lead alloys attain the required creep resistance for the APT T/B operating conditions. All leads and lead alloys investigated proved to attain end-of-life strains >1000%, with the bulk of the data nearing several thousands of percent of strain. However, this conclusion is based on extrapolation of low-temperature creep strain-rate data using the Larson-Miller (L-M) parameter, which is a relationship for time temperature or rate temperature at a constant activation energy (i.e., constant stress). The L-M parameter contains a material constant that generally is known to be universal for many engineering materials, including pure metals. However, closer examination of available (but limited) creep strain-rate data shows that the material constant used in the L-M parameter is not a “constant” and in fact has been estimated as several orders of magnitude lower than the published material constant. Data manipulation of stress-temperature-dependent creep strain rates reveals that the material constant in the L-M parameter varies between 0.1 and 10, with some data scatter in the vicinity of 0.01 to 0.1. However, a majority of the data falls within the range of ~1.0 to 5.0, whereas published information specifies the material constant as 20. Furthermore, some data extrapolation in the low-temperature regime shows that the material constant takes on a negative value between -0.1 and -5.0. The range of values calculated from the available lead data is questionable, partly because of the large range of alloying materials and variability of alloy weight percentage, which have a tremendous effect on the creep characteristics.

More importantly, the inconsistency of limited available data combined with the lack of “hard” data precludes a meaningful engineering analysis of low-temperature creep effects from being extrapolated into the elevated temperature range of APT.

Notwithstanding these arguments, evidence of creep strains using the modified L-M material constant data, as presented in Sec. 5.3 and in App. B, shows that lead creep is a concern with this design. Magnitudes of 2% creep strain over the life of the material cannot be withstood because of a loss of cooling efficiency.

Based on the findings presented in this report, the following recommendations are provided.

- Conduct a series of creep tests on an American Society for Testing and Materials lead specimen containing the actual lead chemistry as required by the neutronic design.

- The physics team should provide lead chemistry of other possible lead alloys that may be used in the APT design, and further investigation of these alloys should continue.

- Investigate further the creep-temperature extrapolation mechanism for lead, and propose a definitive parameter and material constant for high-temperature extrapolation.

- Redesign the lead T/B modules to a rod bundle concept. With this concept, the lead may be encased in aluminum cylindrical tubes; thus, creep is not a concern. This method does not depend on maintaining close geometric tolerance or low lead temperatures.

- Postpone detailed finite-element analysis of lead modules until final resolution of material and creep issues.

CREEP CHARACTERISTICS OF LEAD AND LEAD ALLOYS FOR USE IN THE ACCELERATOR PRODUCTION OF TRITIUM (APT) TARGET/BLANKET

by

Edward A. Rodriguez

1.0. INTRODUCTION

The Accelerator Production of Tritium (APT) preconceptual design [1] incorporates a modular target/blanket (T/B), which comprises ^{3}He channels surrounded by lead. The lead blanket is a hexagonal design casting that measures 30.48 cm (12 in.) across the flats and ~3 m (118 in.) in height and self-supports its dead-weight. The lead castings are encased in 1/4-in.-thick aluminum canning, which maintains the modularity of the lead castings. Heat generated from the accelerator's high-energy proton beam striking the target requires dissipation from the surrounding material. The lead T/B is cooled by 50°C (122°F) water flowing through 0.35-cm diameter channels, entering at the base and exiting at the upper plenum. The exit-water temperature in the lead is ~104°C (219°F). An internal pressure of 35 psi within the cooling channels imposes slight tensile loads in the lead blanket. Furthermore, because the lead cooling is asymmetric along its vertical axis, gradients develop tensile and compressive thermal stresses.

Lead and some lead alloys generally have a low melting point of ~27°C (620°F). For most pure metals, elevated temperature creep effects are quite pronounced at temperatures of $0.4T_M$ (40% of the absolute melting temperature). However, creep is evident at much lower temperatures but is dominated by totally different mechanisms. Susceptibility for creep therefore is a concern, even at ambient operating temperatures of 20°C (68°C).

Because of internal heat generation from the neutron source, cooling of the lead modules is very important to minimize the amount of creep. Furthermore, because creep is stress-dependent to a power law, minimizing the stress inevitably reduces the amount of creep. The consequence of temperature/stress-induced creep is to create excessive deformations in the lead geometry. High tolerances must be maintained within each cooling channel in the lead blanket region throughout its life to maximize cooling efficiency and minimize creep. The life expectancy of the high-power density lead modules is 2 yr, with a 75% average availability. Low-power density lead modules are farther away from the proton beam source and thus attain lower bulk temperatures. These modules would be less affected by creep effects and may have a longer life expectancy.

Pure lead and lead alloys are investigated herein for possible use in the APT T/B design. Also, a brief summary of metallic creep theory is included for completeness, along with derivations of creep parameters. Certain constraints set by neutronics considerations limit the type of alloying material and the amount of alloy present in the lead T/B. Therefore, the candidate lead material must attain a high degree of creep resistance at low to moderate operating temperatures and yet maintain an adequate physics margin for neutron spallation.

2.0. METALLIC CREEP—THEORY

Most engineering metals exhibit creep and stress relaxation at elevated temperatures. Creep is defined as a time-dependent inelastic deformation at constant stress for a given temperature. The inverse of creep is called stress relaxation, which is a time-dependent load reduction at constant deformation for a given temperature. In metals, the temperatures of relevance to induce creep behavior generally are ~40% of the melting temperature ($0.4T_M$). As such, steels having a melting temperature of ~2400°F would have creep behavior initiated at ~960°F (515°C).

However, metallic creep may not be dependent completely on being subjected to elevated temperatures. Some metals, such as commercially pure titanium, also exhibit creep at ambient temperatures. However, the driving force behind creep is activation energy, or an applied stress. Therefore, at ambient temperatures for some specific metals, a high-enough applied stress may induce creep.

2.1. High-Energy Creep

High-temperature creep behavior has been shown [2,3] to obey rate process theory, which may be expressed as:

$$\dot{\varepsilon}_{cr} = Ae^{-\frac{\Delta Q}{RT}}, \tag{1}$$

where

$\dot{\varepsilon}_{cr}$ = creep strain rate, (t^{-1}),
ΔQ = activation energy,
R = gas constant,
T = absolute temperature, and
A = constant.

The activation energy, ΔQ, for elevated-temperature creep generally is considered to be that for self-diffusion of the material. The activation energy has been shown to be within 38 to $40T_M$. Typical creep curves for many metals and alloys behave similarly, as shown in Fig. 1. The primary creep stage is relatively short and generally is considered to be a transient behavior. Secondary creep commonly is termed steady-state creep because the strain rate remains constant with time. The final stage is tertiary creep, where rupture failure is imminent.

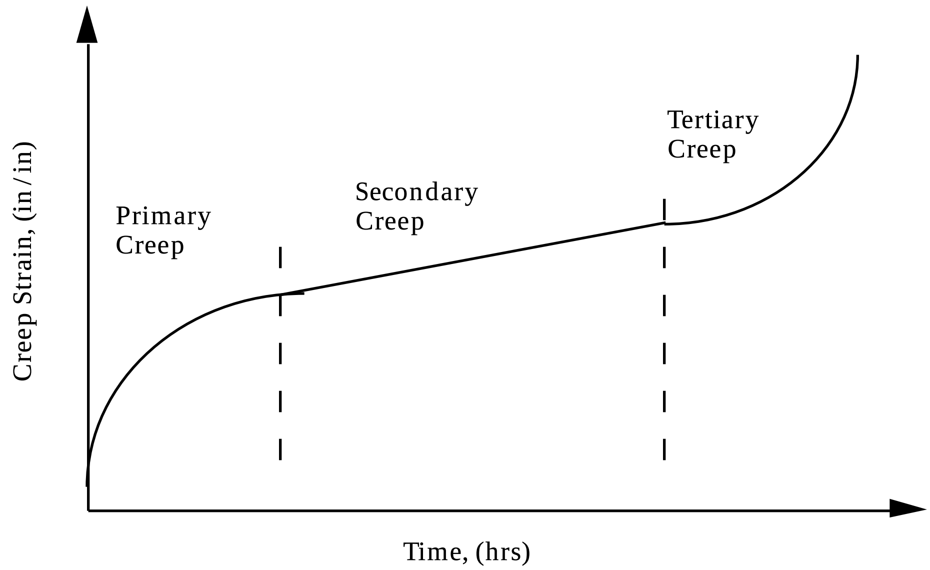

Fig. 1. Creep curve for most metals.

2.2. Steady-State and Transient Creep

Plotted creep strain-rate curves on log-log scales clearly show that most engineering materials exhibit a linear relationship of the form

$$\dot{\varepsilon}_{cr} = \beta\sigma^n \quad , \tag{2}$$

where

β = constant,
σ = stress, and
n = constant.

Both constants, β and n, are material parameters related to the creep behavior and are dependent on the metal temperature. Through creep testing of lead and lead alloys under low-stress conditions, Hofman [4] found that the stress exponent is $\sim n = 4.5$ for pure lead. The magnitude of the exponent reduces from this value of 4.5 (for pure lead) to 3.0 as the amount of alloying element is added to the specimen. Thus, for lead with a very low weight percentage of an alloying element, we would expect a stress exponent of $\sim n = 4.5$.

As stated previously, Eq. (2) represents the creep strain rate as a linear relationship on a log-log scale. Therefore, the total creep strain is a linear relationship with time, assuming a constant stress. That is, the above equation represents the steady-state portion of creep that generally defines several thousand hours (more than 2000 h) under constant stress. Thus, the creep strain is:

$$\varepsilon_{cr} = \beta\sigma^n t \quad . \tag{3}$$

However, as shown in Fig. 1, the total creep strain is not merely linear, but has a transient portion at the outset and a highly nonlinear portion at the end of life. Tertiary creep is enhanced by localized plasticity and necking effects of the material.

Transient creep is of technical significance insofar as to note the beginning of the constant rate, or steady-state, creep. It is also of significance for noting the amount of total creep before initiation of steady-state creep.

The time-hardening power law of transient creep can be expressed as:

$$\dot{\varepsilon}_{cr} = \lambda t^{-m} \quad . \tag{4}$$

Hofman [4] correlated lead and lead-alloy data for high-strain rates and found that the time exponent $m \approx 2/3$.

To completely define the transient portion, as well as the steady-state creep strain rate, the following form provides the required time-dependent parameter in the creep strain-rate equation:

$$\dot{\varepsilon}_{cr} = A\sigma^{n} t^{m} \quad , \tag{5}$$

where

t = time (h), and
m = constant (usually a negative exponent).

If we integrate the strain rate in Eq. (6):

$$\dot{\varepsilon}_{cr} = A\sigma^{n} t^{-m} \quad \text{and} \tag{6}$$

$$d\varepsilon_{cr} = A\sigma^{n} \int t^{-m} dt \quad ;$$

$$\varepsilon_{cr} = A\sigma^{n} \frac{t^{-m+1}}{-m+1} \quad . \tag{7}$$

The third stage of creep is not represented in this form of the equation because it generally is agreed that imminent failure is expected soon after initiation of tertiary creep. As stated previously, necking and localized plasticity play an important role in tertiary creep. As such, engineering designs need only consider transient and steady-state creep effects.

The final creep strain-rate form for pure and low-alloyed lead is approximately

$$\dot{\varepsilon}_{cr} = A\sigma^{4.5} t^{-\frac{2}{3}} \quad , \tag{8}$$

and the creep strain integrated from the above equation is

$$\varepsilon_{cr} = B\sigma^{4.5} t^{\frac{1}{3}} \quad , \tag{9}$$

where

ε_{cr} = creep strain, and
B = constant.

Some error is associated with the above material-dependent parameters n and m. Deviation from these actual values is expected for any data acquisition and for type and weight percent of an alloying element.

3.0. LEAD AND LEAD ALLOYS

The following section provides a brief synopsis of mechanical and physical properties for lead and lead alloys investigated in this report. As mentioned earlier, limitations on the lead and lead-alloy chemistry was imposed by the APT physics constraints. Only a small cross section of leads and alloys are evaluated herein.

Tables 1 and 2 show mechanical and physical properties [5,6,7] that are representative of pure lead and several lead alloys.

4.0. L-M PARAMETER

Time- and rate-temperature relationships may be developed for creep and creep rupture testing from the fundamentals of rate process theory [8]. Because creep is a rate process that obeys the form in Eq. (10), a rate- or time-temperature relationship may be derived for a constant activation energy;

$$\dot{\varepsilon}_{cr} = Ae^{-\frac{\Delta Q}{RT}} \quad , \tag{10}$$

where,

$\dot{\varepsilon}_{cr}$ = creep strain rate,
ΔQ = activation energy,
R = gas constant,
T = absolute temperature, and
A = constant.

TABLE 1
ROOM TEMPERATURE (RT) MECHANICAL PROPERTIES

Property	Pure Lead	Common	Pb-Cu	Pb-Ca	Pb-Sb
Tensile Strength (psi)	1800	1930	2500	5400	3000
Yield Strength (psi)	800	860	1000	2400	1300
Elastic Modulus (psi)	2E+6	2E+6	2E+6	2E+6	2E+6
Elongation (%)	30–47	34	45	30–45	48
Poisson's Ratio	0.40–0.45	0.40–0.45	0.40–0.45	0.40– 0.45	0.40–0.45
Hardness (Brinell or Rockwell)	3.2–4.5B	-----	4 - 6B	70–80R	7B
Impact Strength (ft-lb)	10.4	-----	8 - 12	-----	-----

TABLE 2
PHYSICAL PROPERTIES

Density (lb / in.^{3})	0.409
Specific Gravity	11.37
Melting Point (°F)	621.3
Thermal Expansion Coefficient (/ °F)	16.3E-6
Thermal Conductivity (Btu / ft-h-°F)	20.0
Specific Heat (Btu / lb-°F)	0.0309

Then, by taking logarithms of both sides of Eq. (10),

$$\log\left(\dot{\varepsilon}_{cr}\right) = \log\left(A e^{-\frac{\Delta Q}{RT}}\right) ,$$

$$\log\left(\dot{\varepsilon}_{cr}\right) = \log(A) + \log\left(e^{-\frac{\Delta Q}{RT}}\right) ,$$

$$\log\left(\dot{\varepsilon}_{cr}\right) - \log(A) = -\frac{\Delta Q}{2.305RT} ,$$

or

$$\frac{\Delta Q}{2.305R} = T\left(C - \log\left(\dot{\varepsilon}_{cr}\right)\right) \quad .$$

When a constant activation energy is maintained,

$$T\left(C - \log\left(\dot{\varepsilon}_{cr}\right)\right) = Const. \tag{11}$$

Then, a simple relationship exists such that

$$T_1\left(C - \log\left(\dot{\varepsilon}_{cr_1}\right)\right) = T_2\left(C - \log\left(\dot{\varepsilon}_{cr_2}\right)\right) \quad , \tag{12}$$

where

C = material constant ≈ 20,
T = absolute temperature, (°R), and
$\dot{\varepsilon}_{cr}$ = creep strain rate, (in./in./h).

With the above expression [Eq. (12)] and given a constant activation energy, a creep rate-temperature relationship may be extended to obtain data in regions where data are unavailable. In other words, given a certain creep rate and temperature for a given activation energy, a higher creep rate may be extrapolated for some higher temperature. If we rearrange terms and solve for the creep strain rate at T_2,

$$\log\left(\dot{\varepsilon}_{cr_2}\right) = C - \left[\frac{T_1}{T_2}\left(C - \log\left(\dot{\varepsilon}_{cr_1}\right)\right)\right] \quad . \tag{13}$$

A similar philosophical argument is posed to determine a time-temperature relationship by allowing the "rate" to be an inverse time parameter. That is, Eq. (1) would be

$$\frac{1}{t} = Ae^{-\frac{\Delta Q}{RT}} \quad . \tag{14}$$

If we use a similar procedure as shown above, the L-M parameter becomes

$$T\left(C + \log(t)\right) = Const. \quad , \tag{15}$$

or

$$T_1\left(C + \log\left(t_1\right)\right) = T_2\left(C + \log\left(t_2\right)\right) \quad . \tag{16}$$

The above procedure is worth noting because accelerated creep testing is performed by increasing the test temperature and calculating the time required to perform a test that normally would require many years. That is, if creep strain data are required for a material that will be in service for 10 yr at constant stress under a temperature of 100°F, it would not be economical to perform a 10-yr test. Rather, the test temperature would be increased accordingly to satisfy a shorter time interval.

As such, given the known operating temperature and the length of time in service, the elevated temperature required to perform the test in 1 or 2 yr can be calculated.

The material constant C was chosen by Larson and Miller to represent best a complete cross section of engineering materials, including pure metals, based on creep rupture time. Although these material constants refer to values between 18 and 23 for the material constant, the value of 20 largely has been accepted by the engineering community as representative of numerous materials. Furthermore, whereas Larson and Miller refer to the material constant C as being of equivalent numerical value (regardless of whether the creep rate-temperature or creep rupture time-temperature relationship is used), Finnie and Heller [2] adopted the idea that the numerical values are different, although they did not define the actual numerical value for the creep rate-temperature constant clearly. The discrepancy will become very important in assessing extrapolated creep strain-rate results.

Although this report deals specifically with extrapolation of creep strain-rate data using the L-M parameter, the unavailability of other extrapolation parameters is not implied. On the contrary, there are a handful of extrapolating parameters, each with their own idiosyncrasies and with specific limitations and ranges of applicability. The L-M parameter was used herein because of its wide acceptance in the engineering community.

5.0. RESULTS OF LEAD AND LEAD ALLOYS INVESTIGATION

5.1. Comparison of Creep Strain Rates

Table 3 shows a comparison of available creep strain-rate data at RT for the alloys evaluated in App. B. For uniformity in comparison, a constant stress of 50 psi was used to evaluate the end-of-life creep strains for the APT T/B design at the elevated temperature of 104°C (219.2°F). Results are presented as creep strain rates and subsequent creep strains at the end of life for the 2-yr period at 75% availability.

The L-M parameter was used to extrapolate the low-temperature creep strain-rate data to the elevated temperature of 104°C, with the L-M material constant set at the generally accepted value of 20. As previously stated, this material constant appears to be the key questionable element regarding the results.

The results of Table 3 show both unpromising and disturbing creep strain rates for the low-stress, high-temperature condition of the APT T/B. Intuitively, the results appear to be inconsistent with limited high-temperature data. Secondly, the results appear to show that lead attains a tremendous creep rate at temperatures of $0.3T_M$, which is inconsistent with the known behavior of pure metals. Nevertheless, although there are questionable aspects, the results of Table 3 are presented as documentation of findings but are considered severely suspect.

5.2. Creep of Pb-0.1% Ca for Normal Operating Conditions

Appendix B presents results for a lead-calcium alloy showing that to achieve a 1% creep strain at a constant 50-psi stress over the life of the lead module (i.e., 13,000 h operation), the required lead temperature must be 75°F (23.9°C).

TABLE 3
CREEP STRAIN AND STRAIN-RATE COMPARISON FOR
13,000 h AT 50-psi CONSTANT STRESS, L-M CONSTANT C = 20

	Creep Rate (%/h)		Creep Strain (%)	
	Temperature			
Alloy	**20°C**	**104°C**	**20°C**	**104°C**
Pb (Pure)	1.4E-5	13.1	0.18	170,000
Commercial	3.1E-5	24.8	0.41	322,400
Pb-0.1% Ca	3.4E-5	26.7	0.45	347,000
Pb-0.4% Ca	8.6E-6	9.08	0.11	118,000
Pb-0.5% Sb	1.0E-5	10.46	0.13	136,000
Pb-0.1% Cu	1.0E-6	1.71	1.3E-2	22,240
Pb-2.0% Sn	1.4E-5	13.1	0.18	170,000
Common Pb	1.25E-5	12.2	0.16	158,400
Pb-Te-As	2.1E-7	8.5E-3	3.0E-3	110

Results show that the strain rate at 68°F (RT) is approximately less than half that at 75°F. This means that a mere 7°F increase produces a doubling effect on the creep strain rate.

Figure 2 shows expected creep strain rates and axial temperatures under normal operating conditions. The plot depicts the maximum lead temperature occurring ~31 cm above midheight and the maximum creep strain rate occurring ~10 cm above midheight of the lead module. This is consistent with thermal-hydraulics analysis of the lead modules.

The strain rates are extremely high for continuous normal operation of the APT. Total creep strains developed over the life of the T/B are shown in Fig. 3, and it is evident that the total strains far exceed normal or practical design considerations. Comparing the data of Fig. 2 and 3 with the tellurium-bearing arsenical lead evaluated in App. B, we find that the end-of-life creep strain for the Pb-0.1% Ca is 67 times larger than the tellurium-bearing arsenical lead alloy data depicted in Figs. 4 and 5.

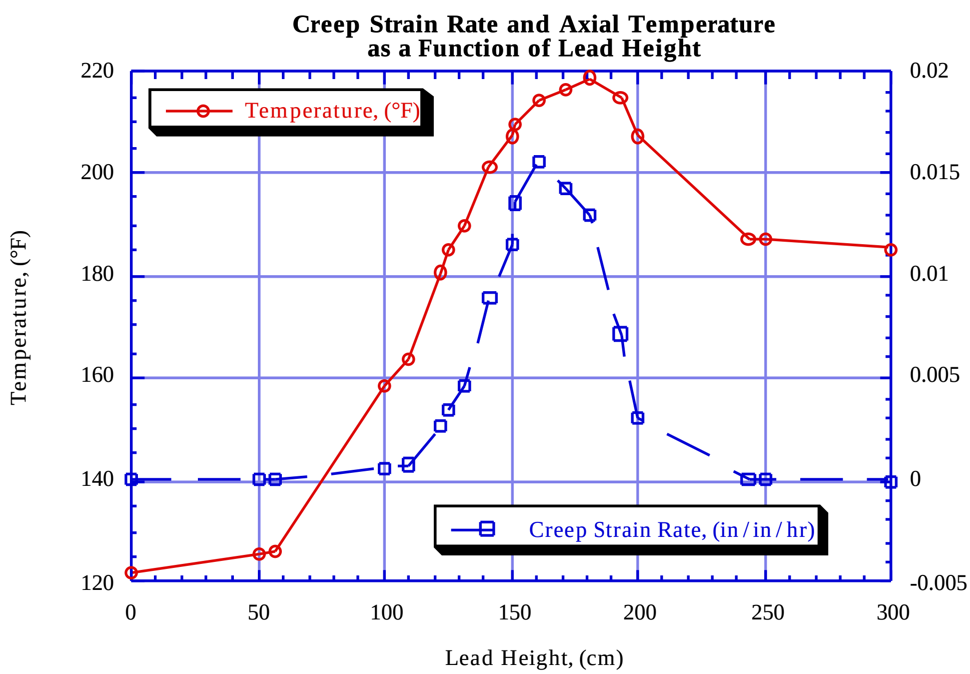

Fig. 2. Creep strain rate and axial temperature vs lead height for Pb-0.1% Ca.

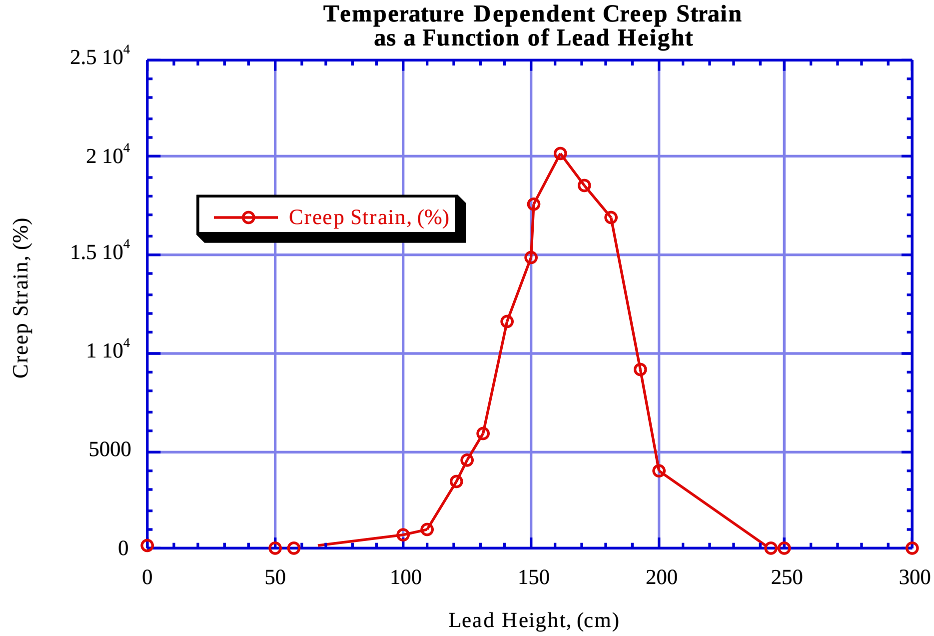

Fig. 3. Creep strain vs lead height for Pb-0.1% Ca.

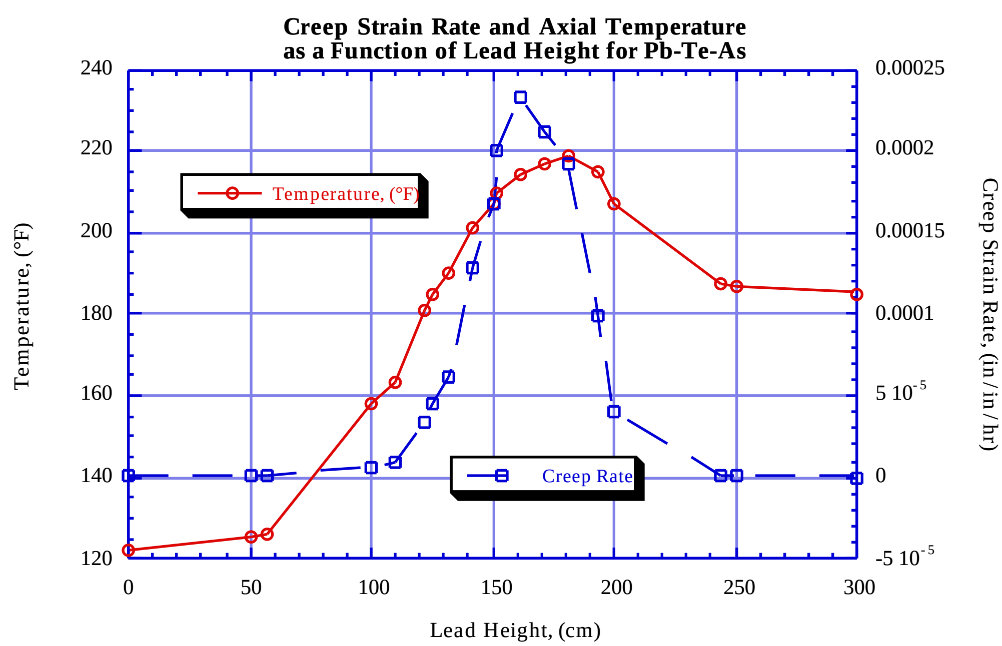

Fig. 4. Creep strain rate and axial temperature vs lead height for the tellurium-bearing arsenical lead.

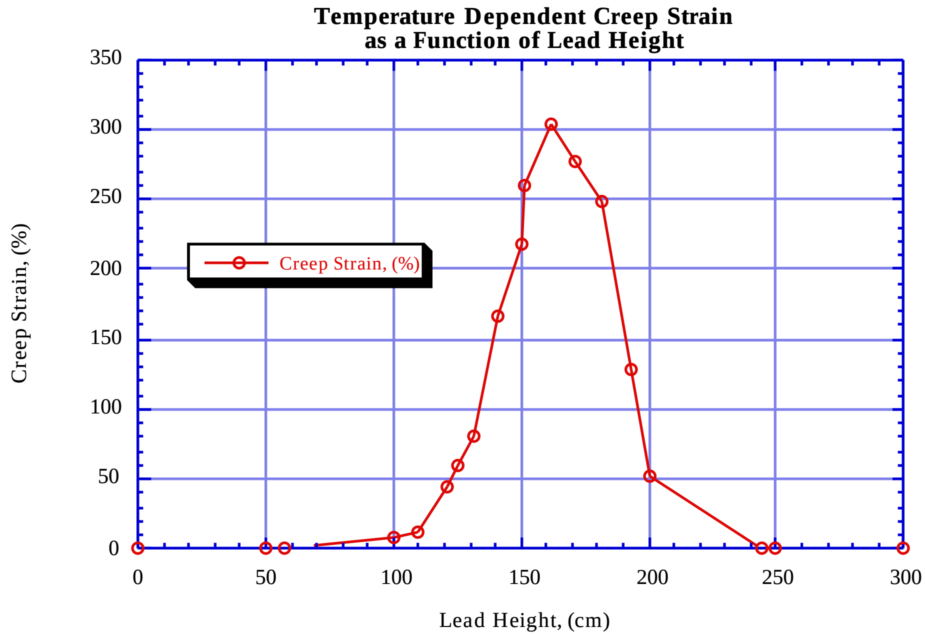

Fig. 5. Creep strain vs lead height for the tellurium-bearing arsenical lead.

5.3. Comparison with Metallgesellschaft Data[7]

Based on the inconsistency found with the published value of the L-M material constant for lead, a more representative value of 1.0 will used for reanalyzing and re-reporting the preceding results. The rationale for presupposing that the currently accepted value of the L-M material constant is incorrect is formulated in App. B. No definitive available data exists for the L-M material constant for lead in extrapolating creep strain rates. However, the results presented in Table 4 generally agree with limited long-term creep strain-rate information published by Metallgesellschaft [7].

The overall creep strains are >1% for the life of the material. These types of results undoubtedly would not maintain adequate geometric tolerances for the cooling channels. We performed a similar analysis of the lead as a function of applied stress and height, given the temperature profile of APT T/B; the creep strain rate and the creep strain are shown in Figs. 6 and 7.

The maximum creep strain over the life of the lead module (~13,000 h) is ~2.5% and occurs at the base of the module.

TABLE 4
CREEP STRAIN AND STRAIN-RATE COMPARISON FOR 13,000 h AT 50-psi CONSTANT STRESS, L-M CONSTANT C = 1.0

	Creep Rate (%/h)		Creep Strain (%)	
	Temperature			
Alloy	**20°C**	**104°C**	**20°C**	**104°C**
Pb (Pure)	1.4E-5	7.7E-4	0.18	10.3
Commercial	3.1E-5	1.5E-3	0.41	19.3
Pb-0.1% Ca	3.4E-5	1.6E-3	0.45	20.4
Pb-0.4% Ca	8.6E-6	5.4E-4	0.11	7.0
Pb-0.5% Sb	1.0E-5	6.2E-4	0.13	8.0
Pb-0.1% Cu	1.0E-6	1.0E-4	1.3E-2	1.3
Pb-2.0% Sn	1.4E-5	7.7E-4	0.18	10.0
Common Pb	1.25E-5	7.2E-4	0.16	9.3
Pb-Te-As	2.1E-7	3.0E-5	3.0E-3	0.39

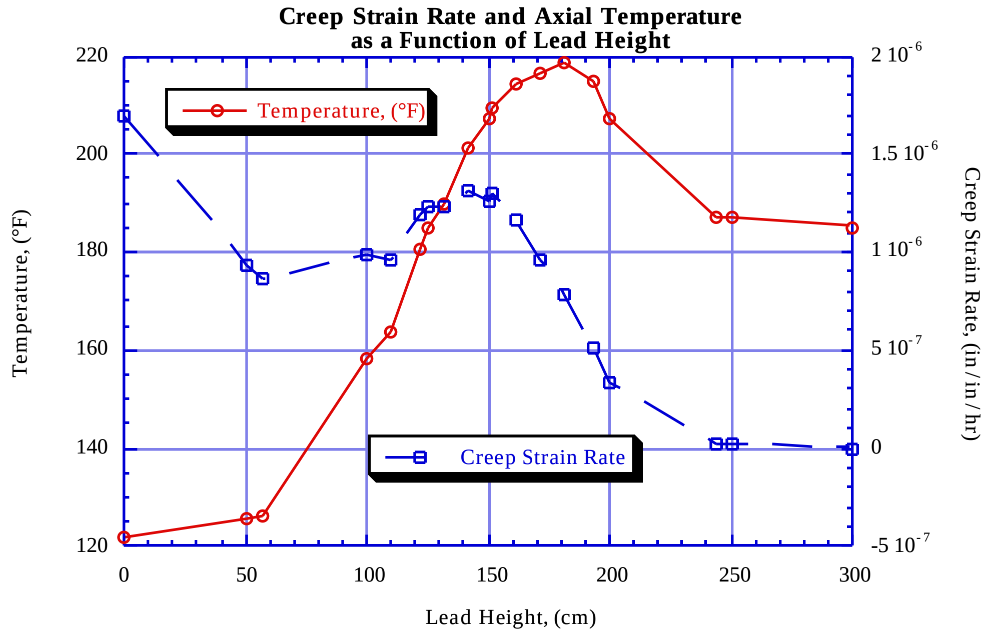

Fig. 6. Creep strain rate and axial temperature vs lead height for Pb-0.1% Ca.

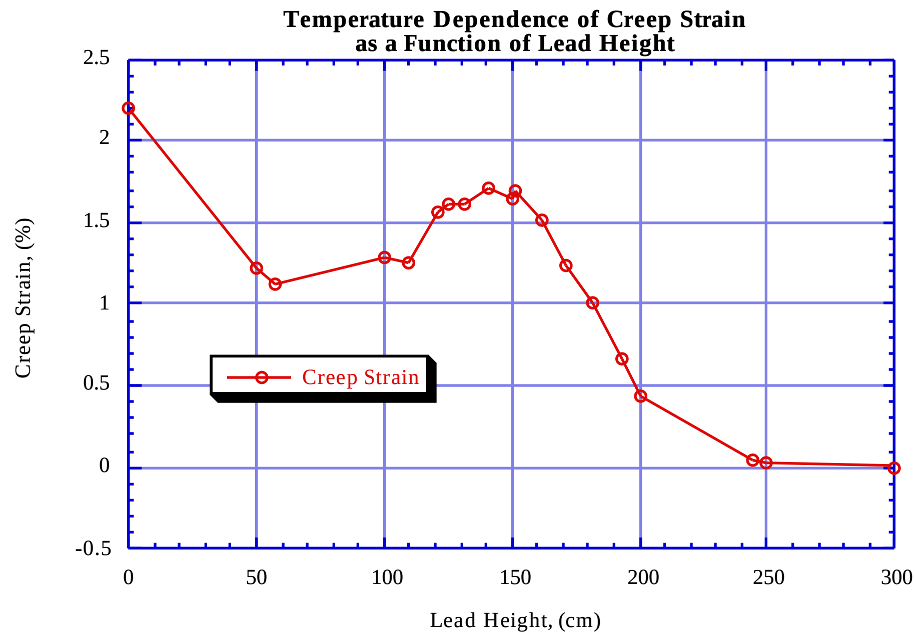

Fig. 7. Creep strain vs lead height for Pb-0.1% Ca.

6.0. CONCLUSIONS

This report presents results of research/investigation into the appropriate lead alloy for use in the APT T/B design that would be capable of minimizing creep strains within the expected maximum overall temperature range of 104°C (219.2°F), applied stresses, and expected life of the T/B. Several lead alloys are reported as potential candidates for the APT design; however, none of these exhibit the creep-resistance characteristic desired for continuous operation of the lead modules at the expected temperature.

- Under normal operating conditions, the candidate lead alloy of choice (Pb-0.1% Ca) far exceeds accepted creep rates and end-of-life creep strains based on the current L-M material constant. The main reason for the excessive strain rates is the temperature dependence, not the applied stress. Lead temperatures at ~104°C are not found in literature for the low weight-percent alloy. For the high temperatures expected in the T/B, lead requires a much higher alloying weight percentage or better alloying elements such as antimony.

- However, the above conclusion should be tempered because the currently accepted L-M creep-temperature extrapolation parameter appears to contain incorrect (or inconsistent) numerical values of the material constant as related to lead or lead alloys. This conclusion is borne out of data manipulation presented in App. B, based on limited high-temperature data published by Metallgesellschaft [7]. The data shows that the L-M material constant for a creep rate-temperature relationship is not the widely accepted value of 20, but rather is between 0.1 and 5.

- Based on the results presented in App. B and reported in Sec. 5.3, it appears that the maximum creep strain for the operating conditions and lifetime of the T/B using a common Pb-0.1% Ca alloy is ~2.5%, which is still not adequate for the current design.

7.0. RECOMMENDATIONS

Based on this report's conclusions:

- A series of creep compression tests should be conducted on a specimen with the actual chemistry of the lead alloy to be used in the APT T/B design.

- The creep tests should be accelerated because of the length of time required for performance. Based on the 2-yr lifetime of the lead modules, a comparable creep test could be conducted at elevated temperatures and stresses and completed within 9 months. The elevated temperature test should not exceed $0.4T_M$.

- Other candidate lead alloys also should be investigated in the event that the preferred lead alloy for the APT T/B design is not acceptable from a creep behavior standpoint. As an example, PbO (lead oxide) should be investigated as a potential material because of its superior melting temperature vs other lead alloys.

- The creep-temperature extrapolation mechanism should be investigated further for lead and a definitive parameter and material constant for high-temperature extrapolation proposed.

- The lead T/B modules should be redesigned to a rod bundle concept such that lead is encased in aluminum cylindrical tubes. This method does not depend on maintaining close geometric tolerance or low lead temperatures.

APPENDIX A

STATE OF STRESS FOR NORMAL OPERATIONS

1.0. STATE OF STRESS FOR NORMAL OPERATIONS

Several different lead alloys are investigated in this report. However, pertinent creep data at the operating temperature of 104°C (219.2°F) are unavailable in literature. There is a wealth of knowledge regarding lead creep in the ambient temperature range of 150°F (65.5°C) for specific alloys [9] with a large alloy weight percentage.

Many applications, such as cable sheathing, storage batteries, and protective structures, are used at relatively low temperatures. Other lead alloy creep data generated in Germany [7] provide relatively high temperatures in the 110°C (230°F) range but are considered unacceptable for the APT T/B from the chemistry standpoint because of their high percentage of alloying elements such as arsenic, antimony, and copper. The APT T/B design is based on maximum overall lead temperatures nearing 104°C (219.2°F); however, the neutronics dictate the alloying element in the lead and the concentration of the alloying element. Therefore, the following information uses available creep data in literature and extrapolates creep rate effects to expected operating temperatures based on expected maximum stresses.

Variability of creep strain rate and creep strains to manufacturing factors is important [10]. Grain-size effects also play a major role in the creep characteristics of lead and lead alloys, along with a history of prior plastic straining.

1.1. Operating Stress

A typical T/B lead module is shown in Fig. A-1. The overall height of the lead is 3 m (118 in.). For scoping calculations, no cooling holes are assumed to exist, which thereby maximizes the overall mass of lead.

Using a mass density of 11.37 kg/cm^3, the maximum bearing stress at the base is

$$\sigma = \rho h \quad ,$$

where,

ρ = mass density,
h = height of lead, and
σ = 50psi .

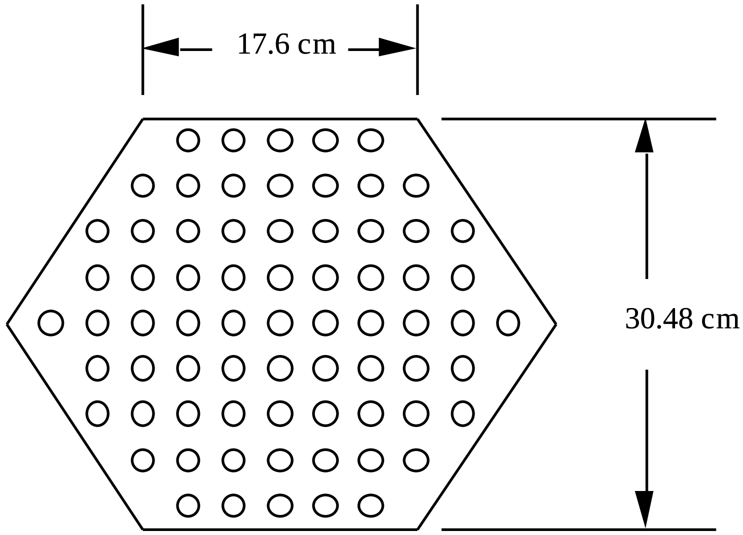

Fig. A-1. Typical lead T/B cross section.

Under normal conditions, we would expect this to be a constant stress at the base of the lead module; however, the bulk of the lead above the base would be at a considerably lower stress, reducing linearly to zero at the top of the lead module. Also, other emergency or faulted conditions may occur during the life of this design. For example, seismic stresses may impose loads with equivalent dynamic amplification factors >2 or 3. This would raise the overall lead-bearing stress to between 100 and 150 psi. However, these are short-lived transient events that do not contribute to overall creep strains throughout the life. Lastly, normal design methodologies dictate using a factor of safety on structural design. If we assume a nominal factor of safety of 2.0 on stress, the overall design stress under normal operating and emergency conditions would be

$$\sigma_{no} = 100\text{psi}$$

and

$$\sigma_e = 300\text{psi} \quad .$$

Furthermore, there are operational stresses imposed on the lead from water pressure in the cooling channels, as well as from thermal stresses developed from temperature gradients along the axis of the module. The pressure-induced stresses are calculated conservatively assuming an equivalent cylindrical section of lead, as shown in Fig. A-2.

The net tensile hoop stress is

$$\sigma = \frac{PR_m}{t} \quad ,$$

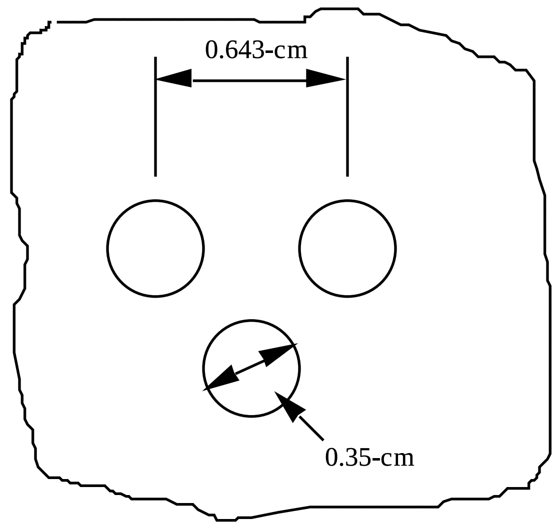

Fig. A-2. Cooling channel geometry.

where

P = pressure (psi),
R_m = mean radius of cylinder (in.),
t = thickness of cylinder (1/2 the ligament thickness in inches),

and actual conceptual design values are

P = 50 psi,
R_m = 0.4965 cm = 0.195 in.,
t = 0.1465 cm = 0.05768 in., and
$\sigma = 170 \text{psi}$.

1.2. Axial Temperature Profile

Figure A-3 represents the thermal profile of the 300-cm (118-in.)-high lead module, which shows a maximum temperature of 104°C at ~181 cm from the base and 50°C at the base; this is compatible with the inlet cooling water temperature.

Although the operational stresses are tensile in nature (i.e., internal water-pressure-induced), the dead-weight-bearing stresses are compressive. Therefore, the lead module undoubtedly will be in a triaxial or biaxial state of stress. The thermal gradients produce no axial stresses because the lead module is unconstrained near the upper plenum. That is, thermal expansion is allowed in the axial direction, which creates axial strain without stress. However, if the lead module were constrained axially, the thermal expansion would create a net compressive stress in the module of

$$\sigma = \alpha E \Delta T \quad ,$$

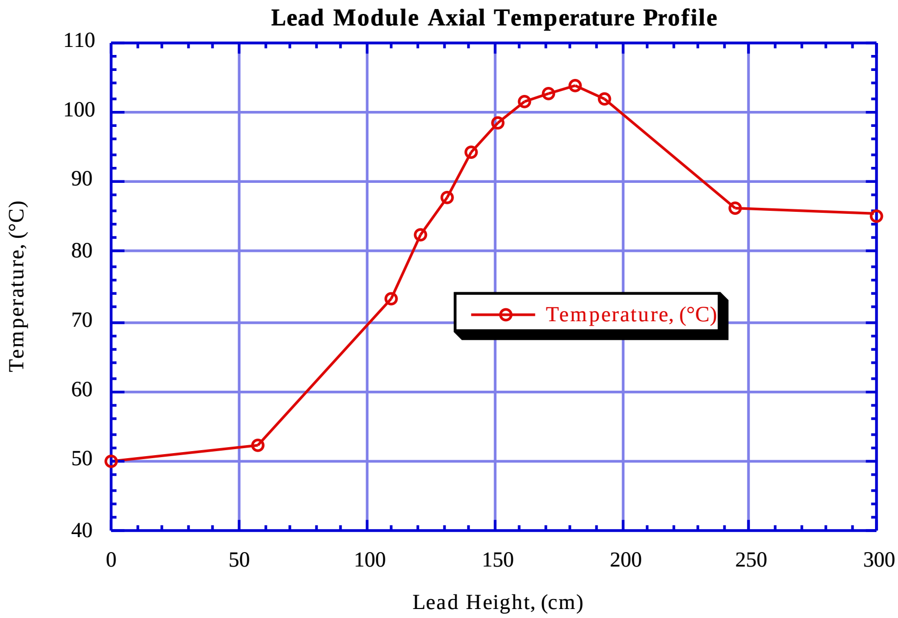

Fig. A-3. Axial temperature profile of lead module.

where

α = coefficient of thermal expansion (in./in./°F),
E = modulus of elasticity (psi), and
ΔT = temperature difference (°F).

If we assume that the bulk temperature of the lead module is 160°F (71.1°C) for the operating conditions shown in Fig. A-4, the net compressive stress developed from the temperature difference between 68 (20°C) and 160°F (71°C) is σ = 3000psi .

This stress exceeds the RT's ultimate tensile strength of lead. Therefore, the lead would be expected to fail immediately.

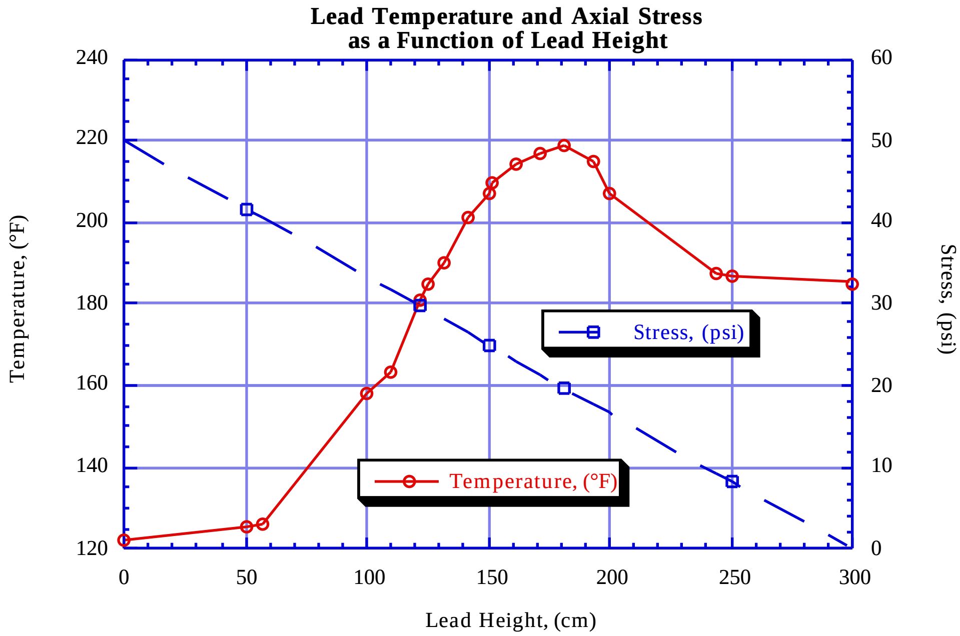

Fig. A-4. Axial stress temperature vs lead height.

The lateral thermal expansion also would induce compressive stresses because the bulk temperature of the low-power density modules would be at temperatures much lower than those in the high-power region. The large mass of low-power density lead far exceeds that of the high-power region; therefore, the overall stiffness of the low-power lead is much higher. As such, lateral expansion is constrained, thereby producing compressive stresses.

The maximum principal stress shown in Fig. A-5 for this case would be

$$\sigma_{\max} = \sigma_{Hoop} - \sigma_{DW} \quad .$$

If we account for sign convention, the maximum principal stress in the high-power density cooling channel is

$$\sigma = 220\text{psi} \quad .$$

Notwithstanding the above arguments, for purposes of investigating the feasibility of some lead alloys in this report, only the dead-weight stresses specified above and shown in Fig. A-4 will be used.

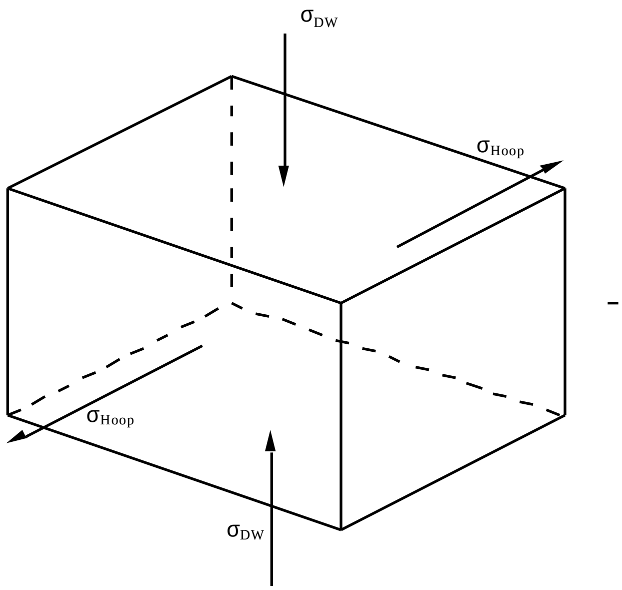

Fig. A-5. Biaxial state of stress.

APPENDIX B

CANDIDATE LEAD ALLOYS CREEP CHARACTERISTICS

1.0. CHARACTERISTICS

1.1. Comparison of Data from Alloy Digest

Some data were obtained from the *Alloy Digest* [5] pertinent to common lead and copper lead (also termed chemical lead). Although copper is unsuitable for the APT design, the data provide a measure of the expected benefit by alloying. Table B-1 below lists several creep strain rates for given stresses and lead composition. The data of Table B-1 further are plotted in Figs. B-1 and B-2.

TABLE B-1
CREEP PROPERTIES FOR COMMON AND COPPER LEAD

	Chemical or Copper Lead Creep (%/h)		Common Lead Creep (%h)
Stress (psi)	**Room Temp.**	**150°F**	**Room Temp.**
200	0.4E-5	6.E-4	0.5E-4
300	1.5E-5	50E-4	3.5E-4
400	3.0E-5	230E-4	11E-4

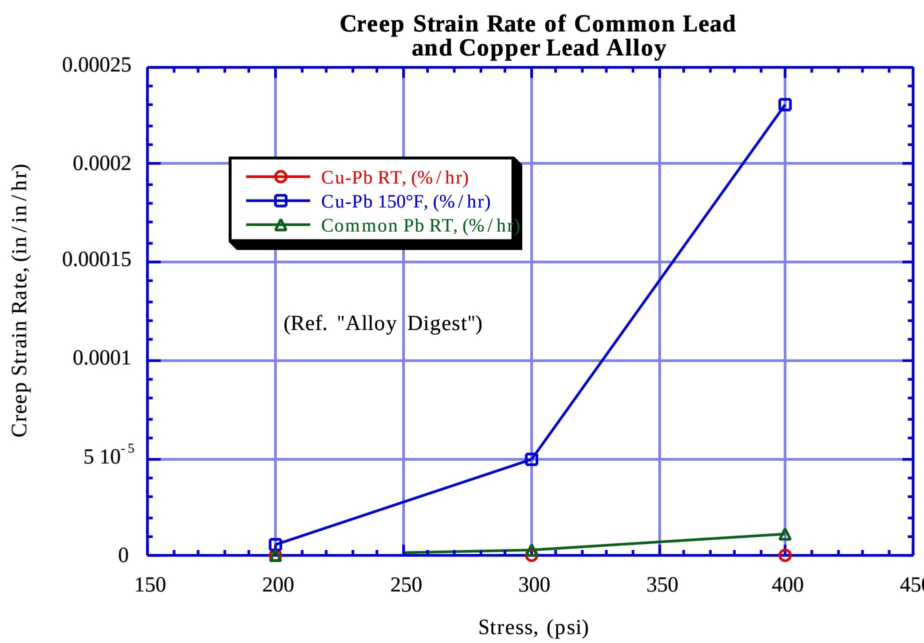

Fig. B-1. Creep strain rate for common and copper lead.

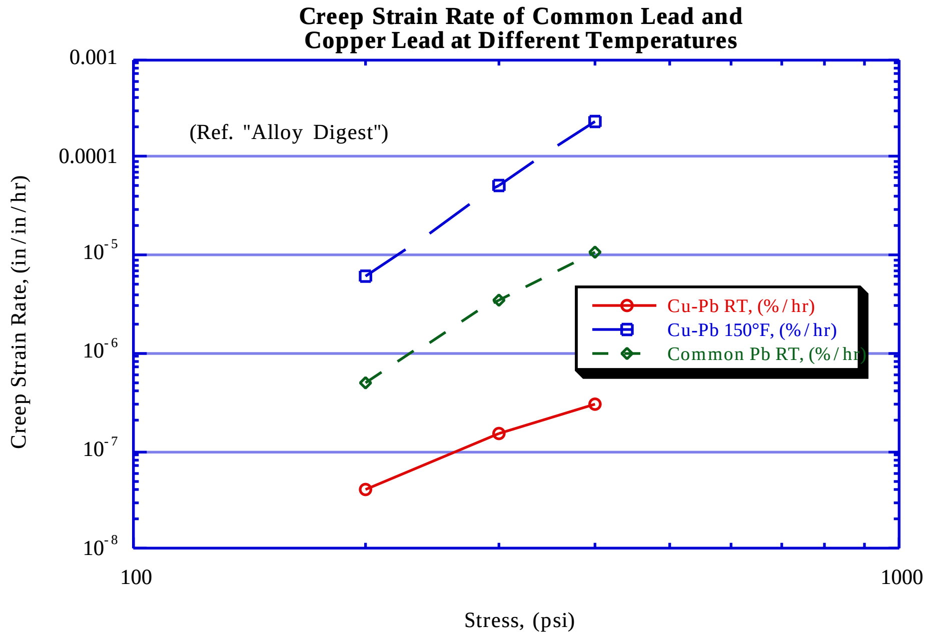

Fig. B-2. Creep strain rate of common and copper lead at different temperatures.

If we linearize the creep strain rate for common lead and for Pb-0.1% Cu, both at RT and 150°F, the estimated creep strain rates are

Pb-0.1% Cu (RT) $$\dot{\varepsilon}_{cr} = (7.5326E-15)\sigma^{2.9301} \quad , \tag{B-1}$$

Pb-0.1% Cu (150°F) $$\dot{\varepsilon}_{cr} = (4.7505E-18)\sigma^{5.2585} \quad , \tag{B-2}$$

and

common lead (RT) $$\dot{\varepsilon}_{cr} = (2.5279E-17)\sigma^{4.4817} \quad . \tag{B-3}$$

The above exponential value seems suspect for all lead alloys, but especially for the Pb-0.1% Cu at 150°F because the stress exponent seems to be outside the range of 3 to 4.5. Because the alloying percentages are similar for both the RT and the 150°F lead-copper specimen, they both should have similar stress exponents. Generally, lead-copper alloys are 99.90% Pb, with the remainder 0.1% Cu. On the other hand, the common-lead specimen, which is almost 99.94% lead, shows an excellent correlation with Hofman's [4] stress exponent for lead at ~4.5 but predicts a strain rate that is two orders of magnitude smaller than pure lead. Therefore, in lieu of using the strain-rate equations (B-1) to (B-3), a linearization of Fig. B-1 data to a 50-psi stress is accomplished. The resulting strain rates in units of inches per inches per hour are:

Pb-0.1% Cu (RT) $\dot{\varepsilon}_{cr} = 1.0E-8$,

Pb-0.1% Cu (150°F) $\dot{\varepsilon}_{cr} = 1.5E-6$, and

common Pb (RT) $\dot{\varepsilon}_{cr} = 1.25E-7$.

If we assume a constant stress of 50 psi, which is representative of APT T/B operating stress, and extrapolate the linearized creep strain rates to the APT T/B design maximum operating temperature of 104°C (219.2°F) by using the L-M parameter [8] of Eq. (B-4) with a material constant of 20, then:

$$\log\left(\dot{\varepsilon}_{cr_2}\right) = C - \left[\frac{T_1}{T_2}\left(C - \log\left(\dot{\varepsilon}_{cr_1}\right)\right)\right] , \qquad \text{(B-4)}$$

where

T = absolute temperature (°R),
$\dot{\varepsilon}_{cr}$ = creep strain rate (in./in./h), and
C ≈ 20.

If we assume a 75% availability for the system, at the end of a 2-yr lifetime (i.e., ~13,000 h) with a constant 50-psi stress, the creep strain rates and total creep strains are listed in Table B-2 below.

The RT specimen appears to exhibit appropriate creep rates for the extrapolated 104°C and 50 psi. The above data show that after a 2-yr lifetime at a constant stress of 50 psi, the lead-copper and common-lead specimens attain creep strains several thousands of percent higher than at RT. The RT results are given at 68°F (20°C). Although this comparison is used only to indicate the dominance that temperature

TABLE B-2
CREEP STRAIN AND STRAIN RATES EXTRAPOLATED TO 104°C FOR 13,000 h

Alloy	Creep Strain Rate (in./in./h)	Creep Strain (%)
Pb-0.1% Cu (RT)	0.0171	22,240
Pb-0.1% Cu (150°F)	6.41E-4	834
Common Pb (RT)	0.122	158,400

has on the creep behavior of alloyed lead, the results appear to be highly suspect. The use of any lead-copper alloy in the APT T/B is not sensible from physics and neutronics standpoints.

1.2. Various Lead Alloys Data

Data obtained from A. H. Sully [3] for various alloying elements and weight percentage of the alloy are itemized in Table B-3 and plotted in Figs. B-3 and B-4. The alloying elements represented are tin (Sn), antimony (Sb), and calcium (Ca).

The effect of creep resistance on alloying pure lead is evident from the data presented in Table B-3. At a constant stress of 200 psi, the pure-lead creep rate is a factor 2.3 higher than the 0.4% Ca alloy lead. At the higher stresses, the effect is much more pronounced because the pure-lead creep rate is a factor of 6.25 higher than the 0.4% Ca alloy.

The linearized log-log scale stress dependence seem quite inaccurate and will not be presented here. Therefore, we will use the actual Table B-3 values for a nominal 50-psi stress, which is comparable to the operating stresses of the APT T/B (without applying a safety factor). When we extrapolate the RT creep strain rate to that of the APT operating temperature, again using the L-M parameter and a material constant of 20:

	Pure Lead	**2% Sn**	**0.5% Sb**	**0.4% Ca**
Strain Rate	13.1	13.1	10.46	9.08
Creep Strain	170,000	170,000	136,000	118,000

TABLE B-3
LEAD ALLOY CREEP DATA AT RT

Tensile Stress		**Creep Strain Rate (%/yr)**			
psi	**kg/cm^2**	**Pure Lead**	**2% Sn**	**0.5% Sb**	**0.4% Ca**
50	3.5	0.12	0.12	0.09	0.075
100	7.0	0.27	0.25	0.19	0.12
200	14.1	0.73	0.64	0.42	0.27
300	21.1	1.63	1.12	0.66	0.43
400	28.1	3.83	1.93	0.94	0.58
500	35.2	7.65	3.20	1.34	0.81
600	42.2	---	7.0	1.81	1.0
700	49.2	---	---	2.41	1.36
800	56.3	---	---	3.39	1.82
900	63.3	---	---	4.85	2.40
1000	70.3	---	---	6.57	3.06

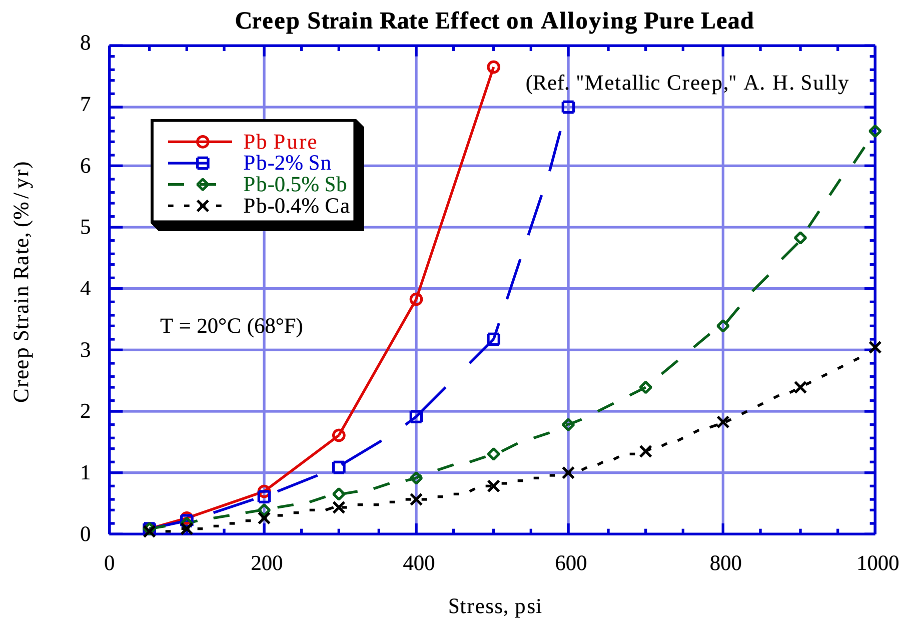

Fig. B-3. Creep strain-rate effect of alloying pure lead—various alloys.

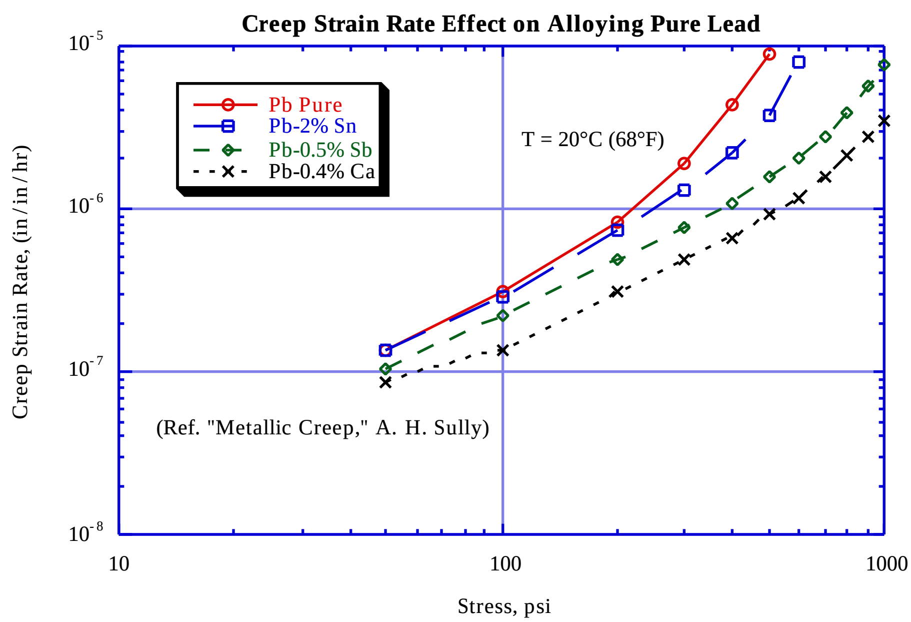

Fig. B-4. Creep strain-rate effect of alloying pure lead with 0.4% Ca.

The numbers presented here show that a total creep strain accumulated after a 2-yr lifetime at 75% availability of $\varepsilon_{cr} = 1180$in./in., or a strain of 118,000% for the 0.4% Ca alloy. Here, either the L-M extrapolation parameter material constant is questionable or this material does not possess the creep resistance at the elevated temperature for the APT.

1.3. Calcium Lead and Commercial Lead

1.3.1. Calcium Lead

As stated previously, the APT T/B design has certain limitations with respect to the specific chemistry of the lead. It has been proposed by the physics team that a 0.1% Ca-impregnated lead would satisfy the neutronics capability for the system. Figure B-5 provides a scattering of lead-calcium data, presumably in the ambient temperature range. The data points relate to different creep specimens, with the weight-percent calcium varying from 0.03 to 0.13%. Therefore, it is expected that the creep strain rate for the Pb-0.1% Ca would be much greater than the Pb-0.4% Ca in App. B.

If we linearize data by using a best-estimate procedure (i.e., “best guess”), Fig. B-6 is developed from available data points. The plot of Fig. B-6 data further can be represented on a log-log scale, as shown in Fig. B-7. It is evident that a linear relationship of the form from Eq. (2) can be derived to represent the steady-state creep portion. The linearized data of Fig. B-7 show the creep strain rate as a function of stress and are approximated as

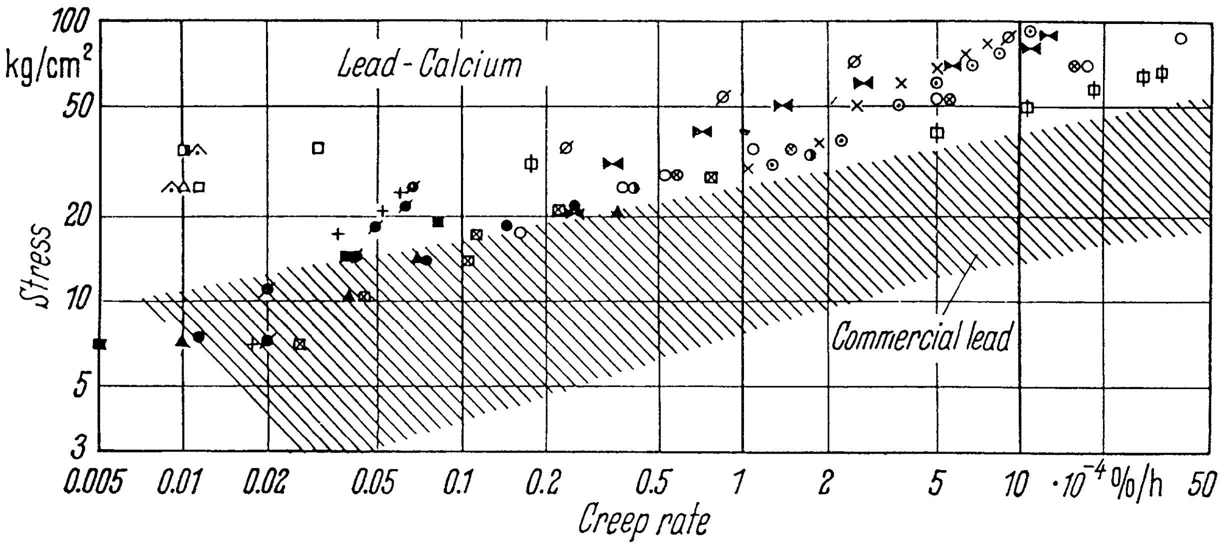

Fig. B-5. Creep rates of Pb-0.1% Ca alloys, (%/h).[4]

$$\dot{\varepsilon}_{cr} = (2.956E-14)\sigma^{4.158} \quad . \qquad \text{(B-5)}$$

Interestingly, the stress exponent is ~4.5, as indicated by Hofman [4]. Furthermore, as the amount of alloying element increases, the exponent reduces to ~3.0. However, the percent of alloying element required to reduce the exponent is unclear from reviewing available data. Nevertheless, close proximity of the stress exponent to 4.5 provides a measure of assurance relative to the lead data.

The extrapolated creep strain rate for Pb-0.1% Ca at a temperature of 104°C and a constant stress of 50 psi is

$$\dot{\varepsilon}_{cr} = 0.267 \text{in./in./h} \quad ,$$

or a total strain after 13,000 h of ~340,000%. This result shows that the strain rate is on the same order of magnitude as the 0.4% Ca-Pb specimen. Thus, this lead alloy will not be adequate for the APT design.

1.3.2. Commercial Lead

Figure B-8 shows creep rate data for commercial-grade lead, which is assumed to be ~99.94% Pb and is similar to common lead. The data again is replotted and shown in Fig. B-9.

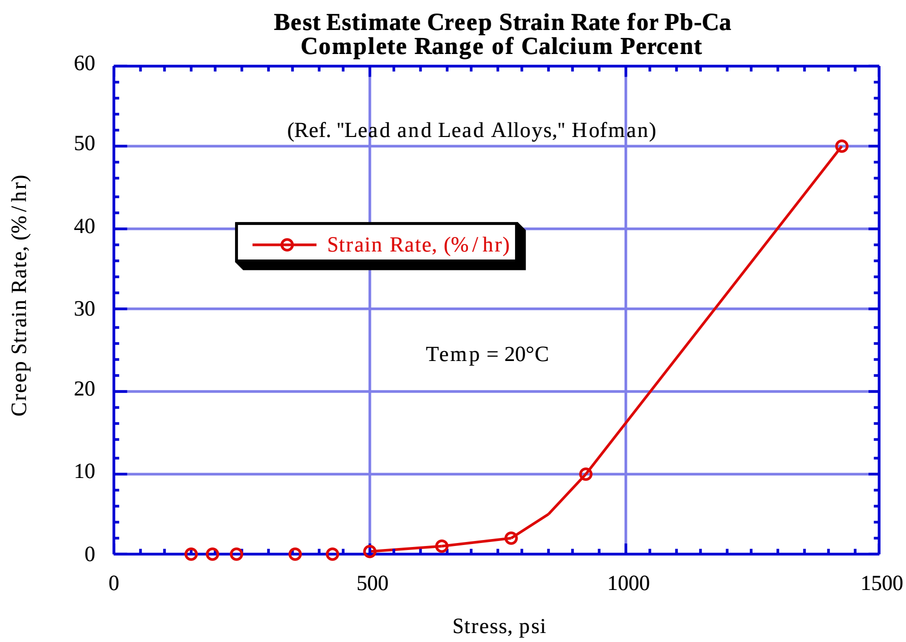

Fig. B-6. Best-estimate creep rates of Pb-0.1% Ca.

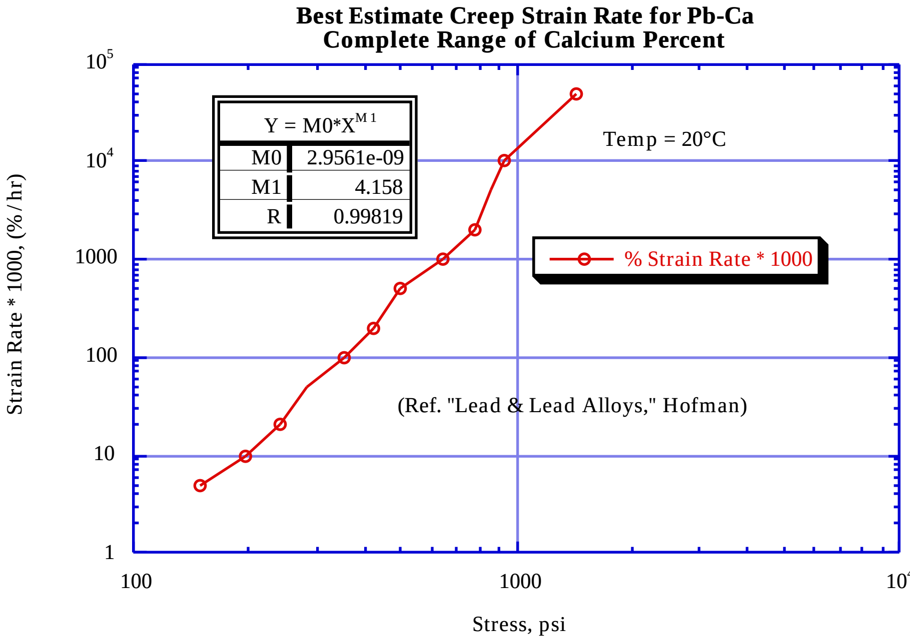

Fig. B-7. Log-log scale best-estimate creep rates of Pb-0.1% Ca.

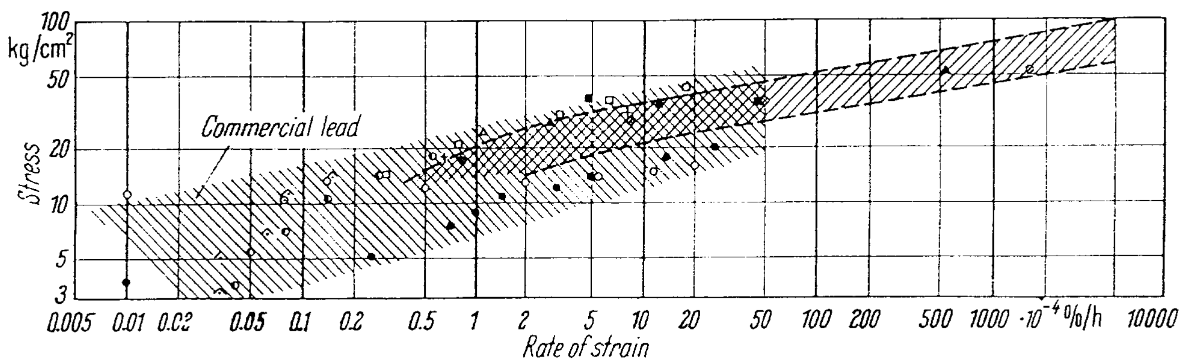

Fig. B-8. Creep rates of commercial lead (%/h) [4].

The linearized steady-state creep rate of Fig. B-9 is estimated to be

$$\dot{\varepsilon}_{cr} = (9.0292E-18)\sigma^{6.2032} \quad ; \qquad \text{(B-6)}$$

for a constant stress of 50 psi, the strain rate is

$$\dot{\varepsilon}_{cr} = 3.124\text{E}-7 \text{in./in./h} \quad .$$

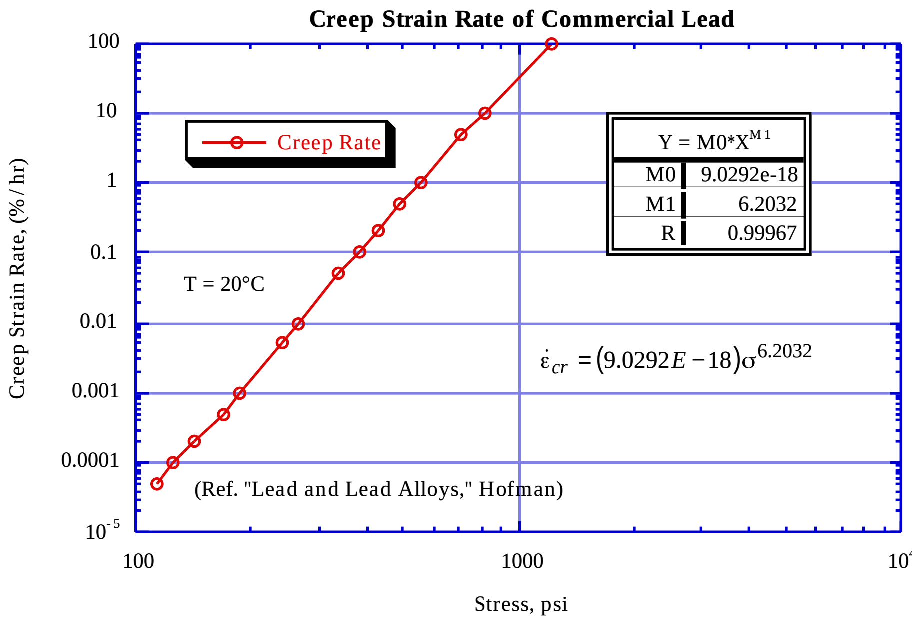

Fig. B-9. Creep strain rates for commercial lead (log-log scale).

The Eq. (B-6) stress exponent appears to be outside the range of theoretical values between 3.0 and 4.5. Nevertheless, the amount of creep strain accumulated appears to be consistent with previous results for the 0.4% Ca-Pb alloy. Therefore, there could be a large error in linearizing data from Fig. B-8.

If we extrapolate the creep strain rate from RT to 104°C at a stress of 50 psi,

$$\dot{\varepsilon}_{cr} = 0.248 \text{in./in./h} \quad .$$

This strain rate is much too great to be meaningful, and as mentioned earlier, there is a potential for the L-M material constant to be inconsistent for lead alloys.

1.4. University of Illinois Data

Figure B-10 presents some data from the University of Illinois [9] that were derived for the cable sheathing industry for tellurium-bearing arsenical lead. The creep tests were conducted at temperatures of 110 and 150°F for variations in applied stress of 150, 200, and 300 psi. The creep data obtained for the 300-psi case at 110°F will be used in this extrapolation because they appeared to achieve a much smoother strain-time relationship than the other creep specimen.

The linearized creep-strain data on a log-log scale of Fig. B-11 becomes

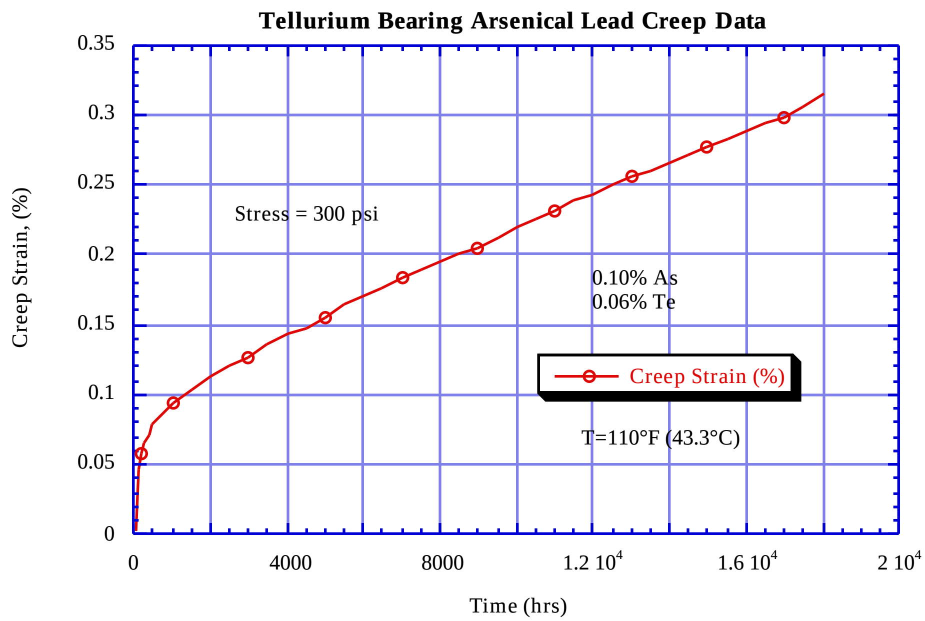

Fig. B-10. University of Illinois data (tellurium-bearing arsenical lead).

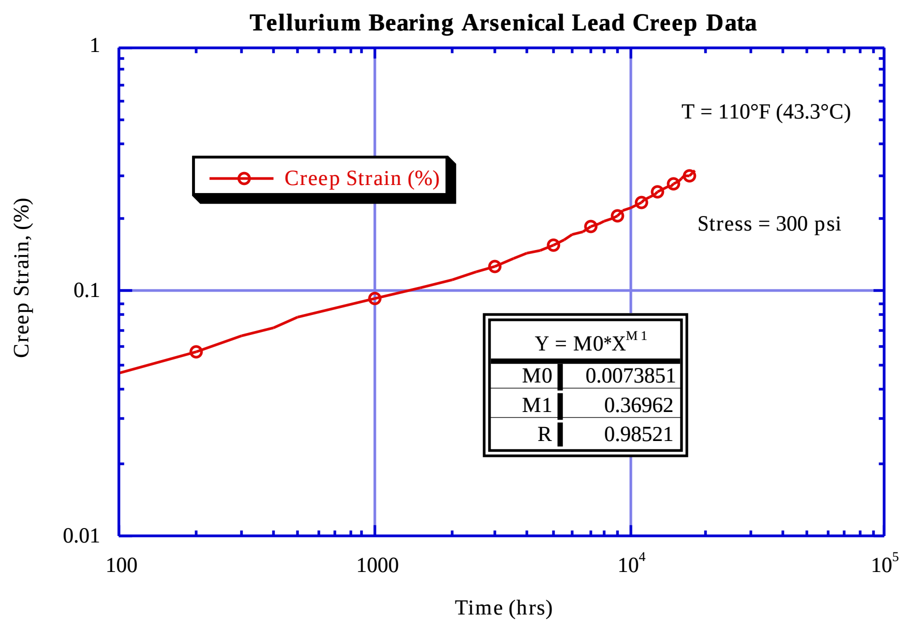

Fig. B-11. University of Illinois data (tellurium-bearing arsenical lead).

$$\varepsilon_{cr} = (7.3851E-3)t^{0.36962} \quad . \tag{B-7}$$

If we differentiate Eq. (B-7), we obtain the transient portion of creep strain rate as

$$\dot{\varepsilon}_{cr} = (2.7297E-3)t^{-0.63038} \quad . \tag{B-8}$$

The accuracy of the time exponent to that predicted by Hofman [4] for lead and lead alloys, i.e., $m \approx 2/3$, is worth noting. The overall creep strain rate, including the steady-state portion, can be assessed from Eq. (6) of the main report by trial and error. Because the applied stress for the creep test was 300 psi, the form of the equation to solve for the constant is

$$\dot{\varepsilon}_{cr} = A(300)^n t^{-0.63038} \quad , \tag{B-9}$$

where

$$A = \lambda\beta$$

and

$$\lambda = 2.7297E-3 \quad .$$

If we assume $n = 4.5$ as an initial guess, the constant A and the actual stress exponent n is derived:

$$\varepsilon_{cr} = (5.0E-14)\sigma^{4.5} t^{0.36962} \quad , \tag{B-10}$$

or

$$\dot{\varepsilon}_{cr} = (1.848E-14)\sigma^{4.5} t^{-0.63038} \quad . \tag{B-11}$$

The creep data conducted by the University of Illinois and presented in this section appear to have been produced with great care because the creep behavior actually is plotted as creep strain vs time. For example, calculating the overall creep strain for 13,000 h of operation from Eq. (B-10) produces the exact strain results. In calculating the same overall creep strain from the strain rate in Eq. (B-11) for 13,000 h, a total strain equal to one-third of that from Eq. (B-10) is obtained. The difference occurs because the creep strain equation employs a defined transient creep portion and therefore is much more accurate.

Other data in this report present only creep strain rate vs stress, which allows those using the data great latitude in making judgments or errors regarding the true nature of the relationship. Now we have a stress-time-dependent equation to extrapolate into the elevated temperature region. Figure B-12 shows the actual data and the mathematical approximation. There is a slight underprediction of the creep strains from ~10,000 h and higher. However, the approximation for the elevated temperature data will provide some quantitative measure of the applicability of this lead alloy for the APT T/B design.

Using the L-M parameter in Eq. (B-4) at 104°C (219.2°F) and given a nominal stress of 50 psi and a material constant of 20, sustained for 13,000 h, we obtain

$$T_1 = 110 + 460 \quad ,$$

$$T_2 = 219.2 + 460 \quad ,$$

$$\dot{\varepsilon}_{cr_1} = 2.083E-9 \quad \text{, and}$$

$$\dot{\varepsilon}_{cr_2} = 8.51E-5 \quad .$$

After 13,000 h, the total creep strain at 104°C would be $\varepsilon_{cr_2} = 1.106 \text{in./in.}$, or 110% strain. The results of this lead alloy predict high overall creep strains at the end of life for the APT T/B module, but much lower overall creep strains than other alloys investigated in this report. Tellurium and arsenic alloys in pure lead provide a tremendous resistance to creep; however, at a material temperature of 104°C, the creep strains are much greater than desired. Therefore, this material is not adequate for the APT design.

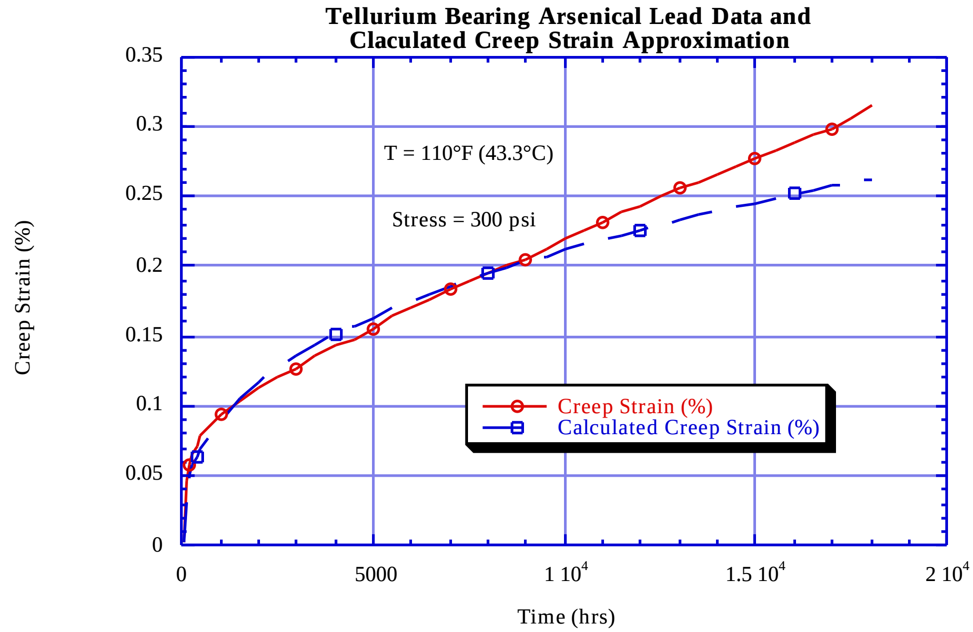

Fig. B-12. University of Illinois data and mathematical approximation of Eq. (B-10).

1.5. Metallgesellschaft Data

Limited creep data is contained in the *Lead Handbook* [7] for temperatures nearing 110°C (230°F). The data are represented as stress vs temperature to cause 1 and 5% creep strain in 50,000 h. Figures B-13 through B-18 show the creep data for high-purity antimonial lead, high-purity copper lead, and several high-strength alloys containing antimony and arsenic. The region of interest for this design is the 104°C temperature, where the stress levels to cause 1 and 5% creep strain vary with material composition from 0.15 to 1 MPa (20 to 145 psi).

Because creep strain rate follows a rate process theory where the low-temperature data can be extrapolated to high temperatures, Eq. (12) may represent a complete rate-temperature history if and only if a constant activation energy is imposed. It therefore follows that if we have information on creep rates and creep temperatures at constant stress levels, then we may express Eq. (12) as

$$T_1\left(C - \log\left(\dot{\varepsilon}_{cr_1}\right)\right) = T_2\left(C - \log\left(\dot{\varepsilon}_{cr_2}\right)\right) \quad .$$

If we solve for the material constant C ,

$$C = \frac{\left(T_1 / T_2\right)\log\left(\dot{\varepsilon}_{cr_1}\right) - \log\left(\dot{\varepsilon}_{cr_2}\right)}{\left(T_1 / T_2\right) - 1} \quad . \tag{B-12}$$

In the case of Figs. B-13 to B-18, the creep strain rates are known because the data are presented as 1 and 5% creep strain over 50,000 h. Also, the creep rates are assumed to be steady-state rates because they exceed several thousand hours:

$$\dot{\varepsilon}_{cr_1} = \frac{0.01\text{in./in.}}{50000\text{h}} \quad \text{, and}$$

$$\dot{\varepsilon}_{cr_2} = \frac{0.05\text{in./in.}}{50000\text{h}} \quad .$$

Temperature extraction from Figs. B-13 through B-19 at constant stress levels will provide T_1 and T_2, for 1 and 5% creep strain, respectively. Therefore, all information required to satisfy Eq. (B-2) is contained in the figures, except for the laborious and time-consuming task of extracting data the “old-fashioned way.”

Results of solving Eq. (B-12) for the numerous alloy leads at different stress levels reveal a scattering of data points for the material constant C. Figures B-19 and B-20 depict the data points for the constant within a specified range, but not within a value of 20. Closer evaluation of the constant C shows that it may range between negative and positive values. However, the bulk of the data falls within 0.1 and 1.0, with some data exceeding 1.0 and nearing a value of 5. Nevertheless, the large scatter is indicative that this parameter “constant” is not a constant value, but rather is a variable.

This clearly shows that, based on limited data, the L-M extrapolation parameter for lead and lead alloys contains a material constant that appears to be at least one to two orders of magnitude lower than currently accepted (published) values.

1.6. Elevated Temperature for 1% Creep Strain

This appendix summarizes creep rate data extrapolated from RT to that of the APT design maximum lead temperature of 104°C (219.2°F). Resulting creep strains for end-of-life operation of the APT T/B all were shown to be much greater than 1000%. It therefore would be beneficial to arrive at an appropriate elevated temperature for the lead module attaining a 1% creep strain after 13,000 h of operation that produces a creep strain rate of

$$\dot{\varepsilon}_{cr_2} = \frac{0.01in./in.}{13000h} \quad ,$$

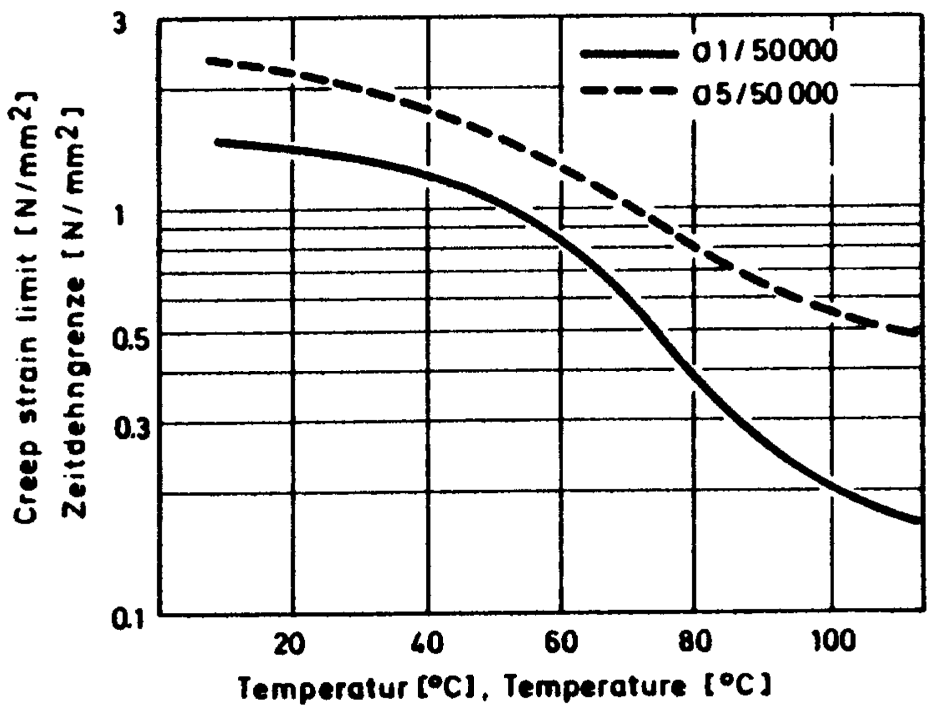

Fig. B-13. High-purity antimonial lead, creep data [7].

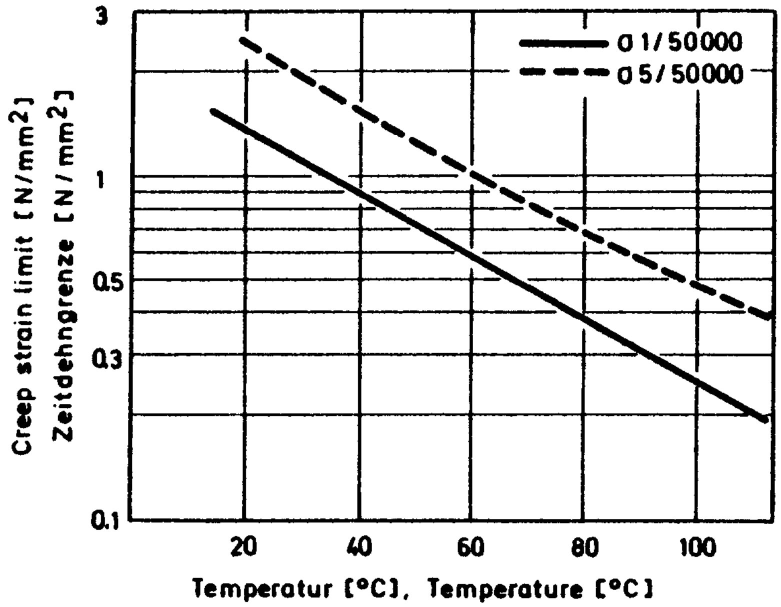

Fig. B-14. High-purity copper lead, creep data [7].

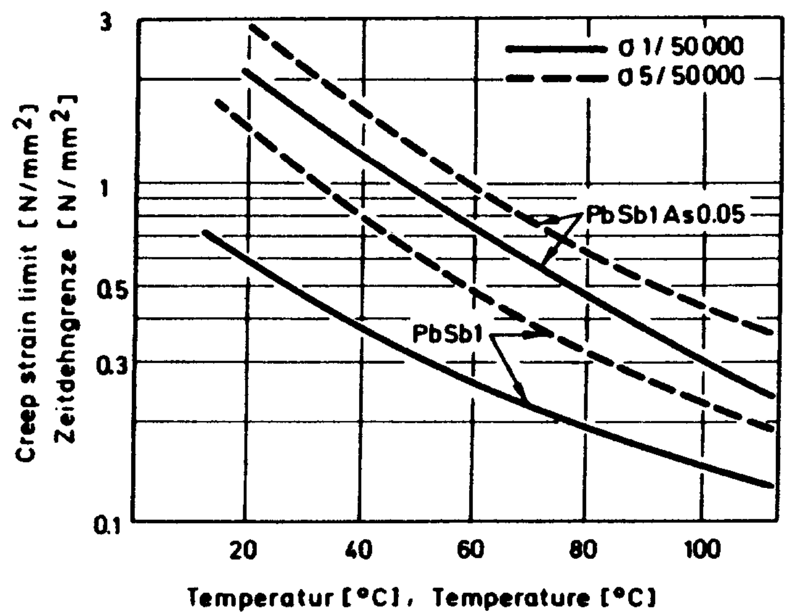

Fig. B-15. Tellurium-bearing arsenical lead, creep data [7].

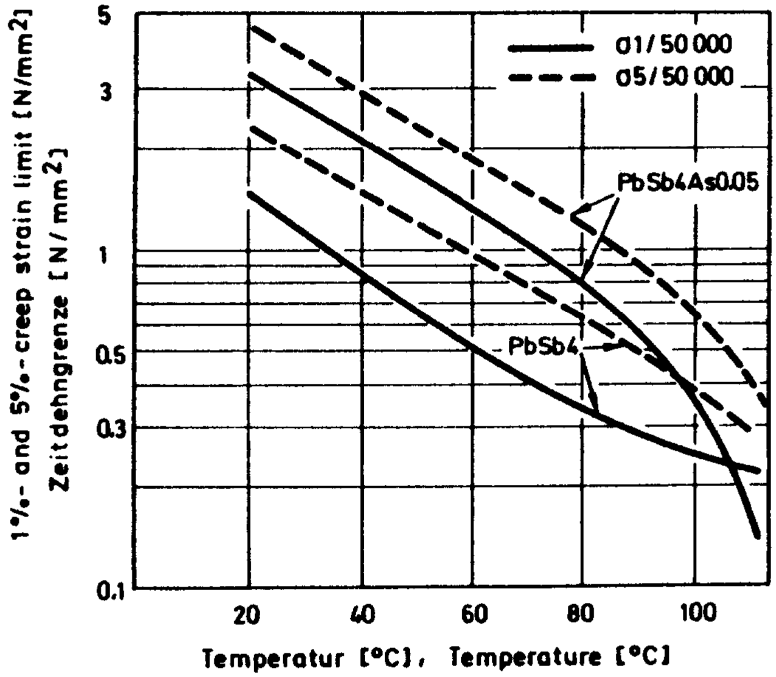

Fig. B-16. Tellurium-bearing arsenical lead, creep data [7].

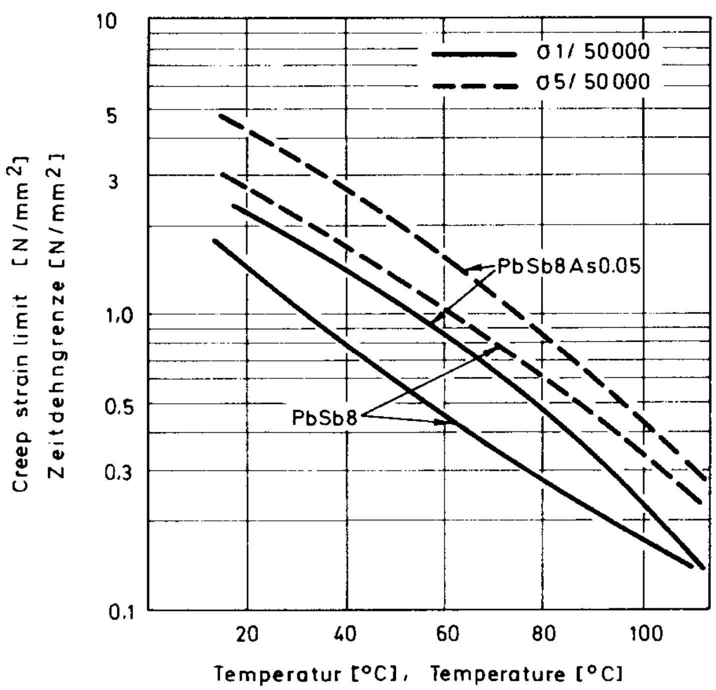

Fig. B-17. Tellurium-bearing arsenical lead, creep data [7].

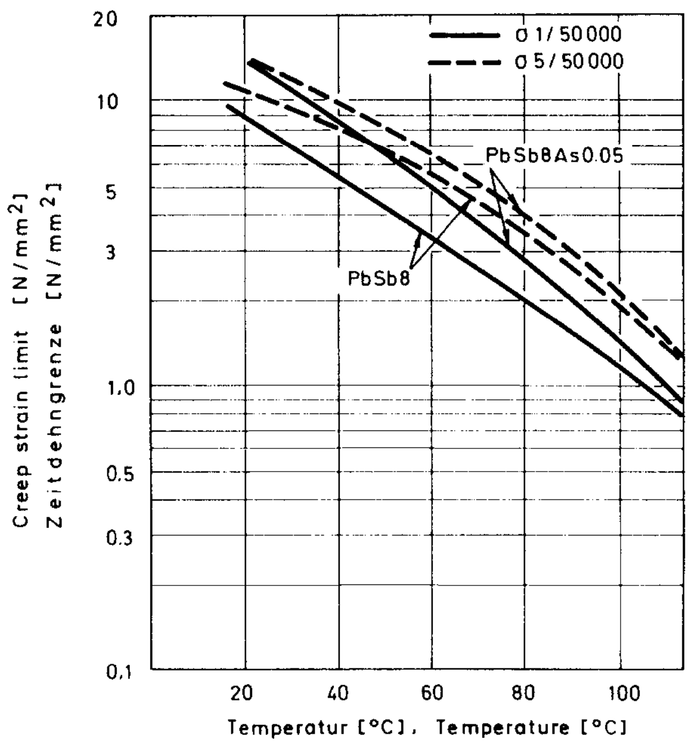

Fig. B-18. Tellurium-bearing arsenical lead, creep data [7].

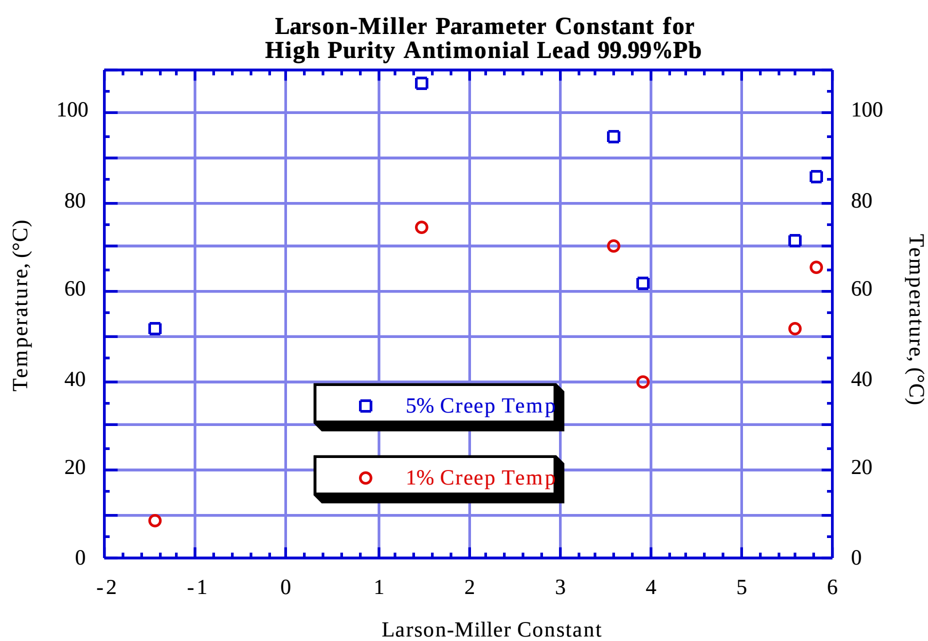

Fig. B-19. L-M material constants for high-purity antimonial lead.

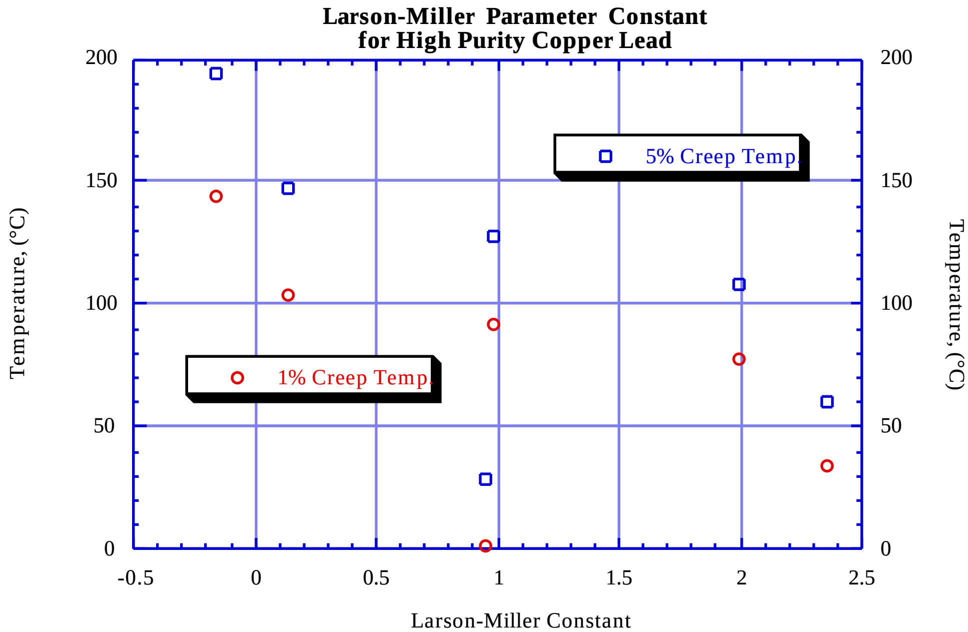

Fig. B-20. L-M material constants for high-purity copper lead.

or

$$\dot{\varepsilon}_{cr_2} = 7.692E - 7 in./in./h \quad .$$

This calculation will provide some insight into the severity of the temperature dependence of lead alloys. If we solve Eq. (12) in the main report for temperature T_2, then given the L-M material constant of 20,

$$T_2 = \frac{T_1\left(20 - \log\left(\dot{\varepsilon}_{cr_1}\right)\right)}{\left(20 - \log\left(\dot{\varepsilon}_{cr_2}\right)\right)} \quad .$$

If we use the Pb-0.1% Ca strain-rate results shown in App. B for RT at a constant stress of 50 psi,

$$\dot{\varepsilon}_{cr_1} = (2.956E - 14)\sigma^{4.158} \quad ,$$

or

$$\dot{\varepsilon}_{cr_1} = 3.428E - 7 in./in./h \quad .$$

The resulting temperature to cause 1% creep strain after 13,000 h of operation would be $T_2 = 535° R$, or $T_2 = 75° F$.

The strain rate at 68°F (RT) is approximately half that at 75°F. A 7°F temperature increase produces a doubling of the creep strain rate. As can be seen from the foregoing calculation, most candidate lead alloys with the required lead chemistry for APT T/B attain inadequate creep resistance.

Now, using the L-M parameter material constant as presented in App. B for a representative value of 1.0, the resulting temperature to cause 1% creep strain after 13,000 h of operation would be

$$T_2 = \frac{T_1\left(1 - \log\left(\dot{\varepsilon}_{cr_1}\right)\right)}{\left(1 - \log\left(\dot{\varepsilon}_{cr_2}\right)\right)} \quad ,$$

where

$$T_2 = 554°R \quad ,$$

or

$$T_2 = 94°F \quad .$$

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