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Title: Plutonium Metallurgy

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Intended for: Seaborg Institute Student Seminar

# Plutonium Metallurgy


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Los Alamos, NM


August 9, 2012

# Reference Materials:

**Plutonium Metallurgy at Los Alamos, 1943-1945: Recollections of Edward F. Hammel,**
E.F. Hammel, Self-published in 1998.

<u>General Metallurgy</u>
**Structure of Metals**, Third Edition: Crystallographic Methods, Principles and Data (International Series on Materials Science and Technology), C.S. Barrett and T. B. Massalski

**Phase Transformations in Metals and Alloys**, 3rd Edition; D. A. Porter, K.E. Easterling, M. Sherif

**Physical Metallurgy Principles** (Prindle, Weber & Schmidt Series in Advanced Mathematics)
R. Abbaschian, R.E. Reed-Hill

<u>Plutonium and Other Actinides</u>
**Challenges in Plutonium Science** (Los Alamos Science, Vol. 1 and 2, Number 26), N.G. Cooper

**"Plutonium," Chapter 7, The Chemistry of the Actinides and Transactinides**, 3rd Edition, Springer, D.L. Clark, S.S. Hecker, G.D. Jarvinen, and M.P. Neu,

**The Metal Plutonium** (University of Chicago Press), A.S. Coffinberry, W.N. Miner

The Series: **Plutonium 1960**, **Plutonium 1965**, **Plutonium 1970**, and **Plutonium 1975**

**Phase Diagrams of Binary Actinide Alloys (ASM Monograph Series on Alloy Phase Diagrams)**
M. E. Kassner, D. E. Peterson

**Plutonium Handbook : A Guide to the Technology, Vol. 1 and 2,** O. J. Wick

# Reference Materials: (cont.)

Plutonium Metallurgical Reports:

**Physical and Mechanical Metallurgy Studies On Delta Stabilized Plutonium-Gallium Alloys** (BNWL- 13, UC- 25), H. R. Gardner (April, 1965), Battelle-Northwest/Pacific Northwest Laboratory,

**Plutonium Metallurgy Notebook** (BNWL- 37, UC- 25), M. E. Hasbrouck, (September, 1965) Battelle-Northwest/Pacific Northwest Laboratory,

**Plutonium Microstructures** Part 1 "Impurities and Inclusions" (UCRL-53174-1, 1981) and Part 2 "Binary and Ternary Alloys" " (UCRL-53174-2, 1983) , E.M. Cramer and J.B. Bergin, Lawrence Livermore National Laboratory

Miscellaneous Report Archive Websites:

http://lasearch.lanl.gov/oppie/service - LANL Research Library Reports

http://arq.lanl.gov/source/orgs/nmt/nmtdo/AQarchive/AQhome/AQissues.shtml - Seaborg Institute for Transactinium Science Publication Actinide Research Quarterly

http://www.osti.gov/bridge/ - Information Bridge: DOE Scientific and Technical Information

http://www.fas.org/sgp/othergov/doe/lanl/ - Los Alamos National Laboratory Reports

http://www.fas.org/irp/agency/dod/jason/ - JASON Defense Advisory Panel Reports

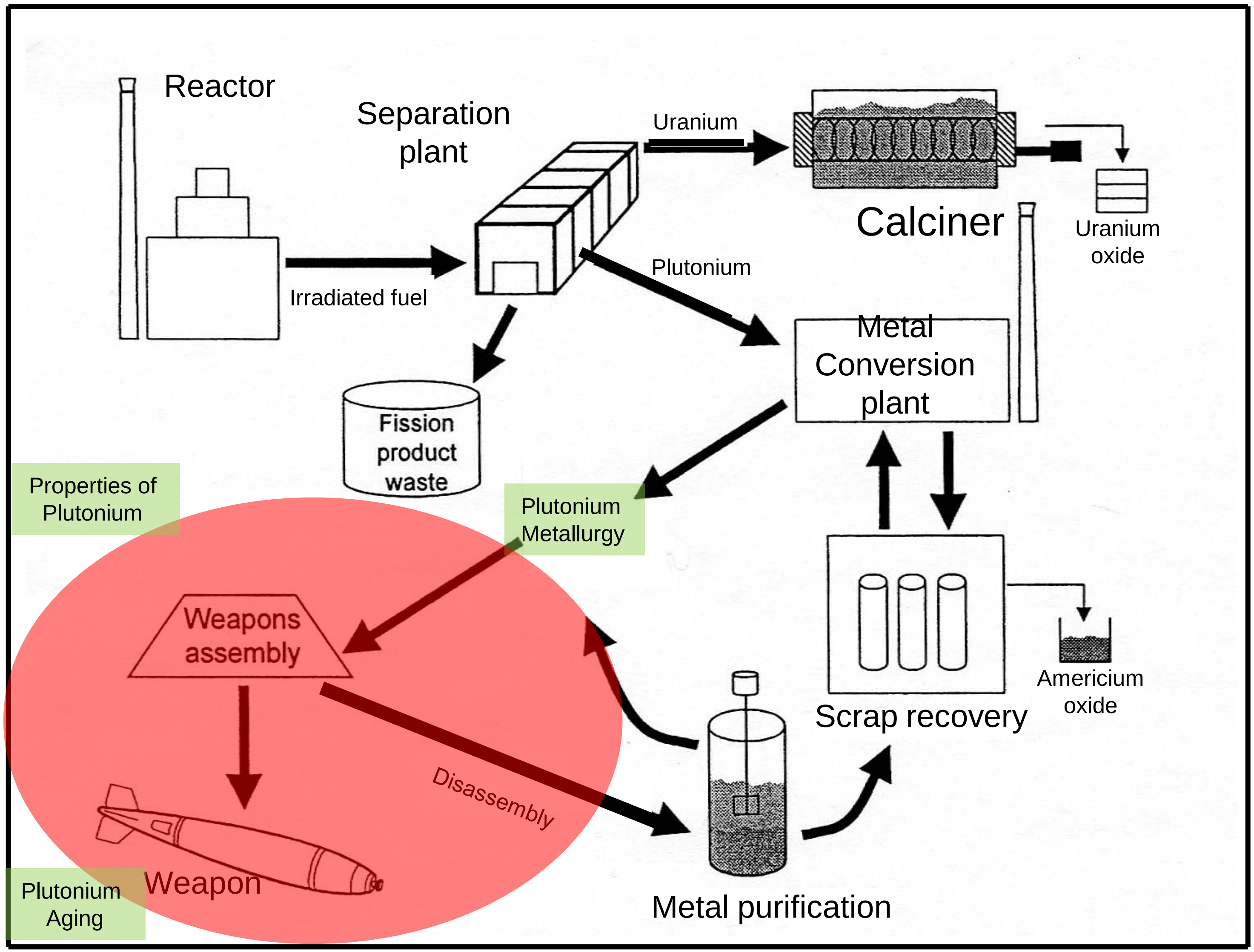
# Plutonium: Materials Science and Technological Uses

# Plutonium Applications

All stem from special nuclear properties of Pu

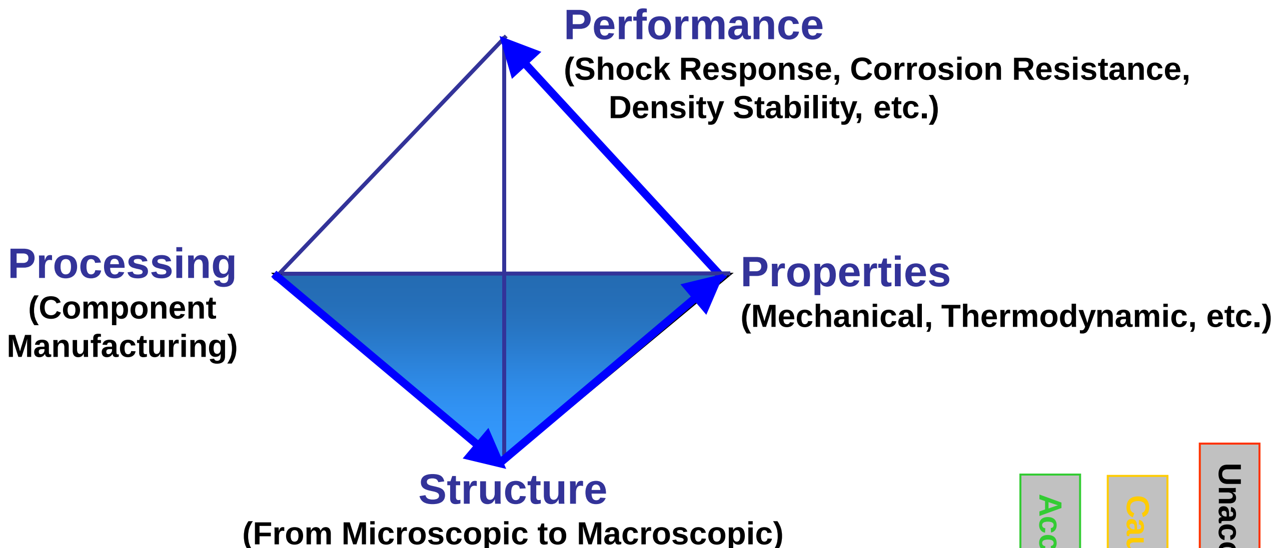
| | |
|---|---|
| **$^{239}Pu$ Metal :** | **Nuclear weapons**<br>**Early nuclear reactors** |
| **$^{239}Pu$ Oxide :** | **Nuclear reactors**<br>**Mixed oxide fuels**<br>**$^{238}UO_2$-20%$^{239}PuO_2$** |
| **$^{238}Pu$ Oxide :** | **Radioisotope heat sources**<br>**Fuel for space power systems** |

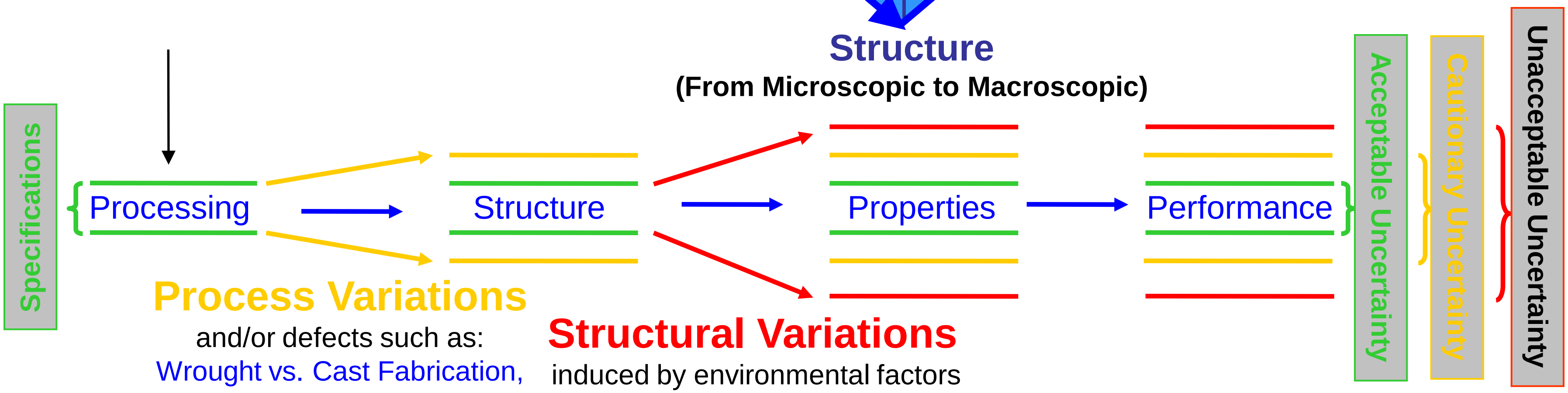
# Plutonium Processing Cycle



# Materials Science Tetrahedron Applied to Weapons Materials

**<u>Established Manufacturing Process</u>**
Known performance and margin based on well-known causal relationship between processing specifications and resultant structure, properties, and performance.



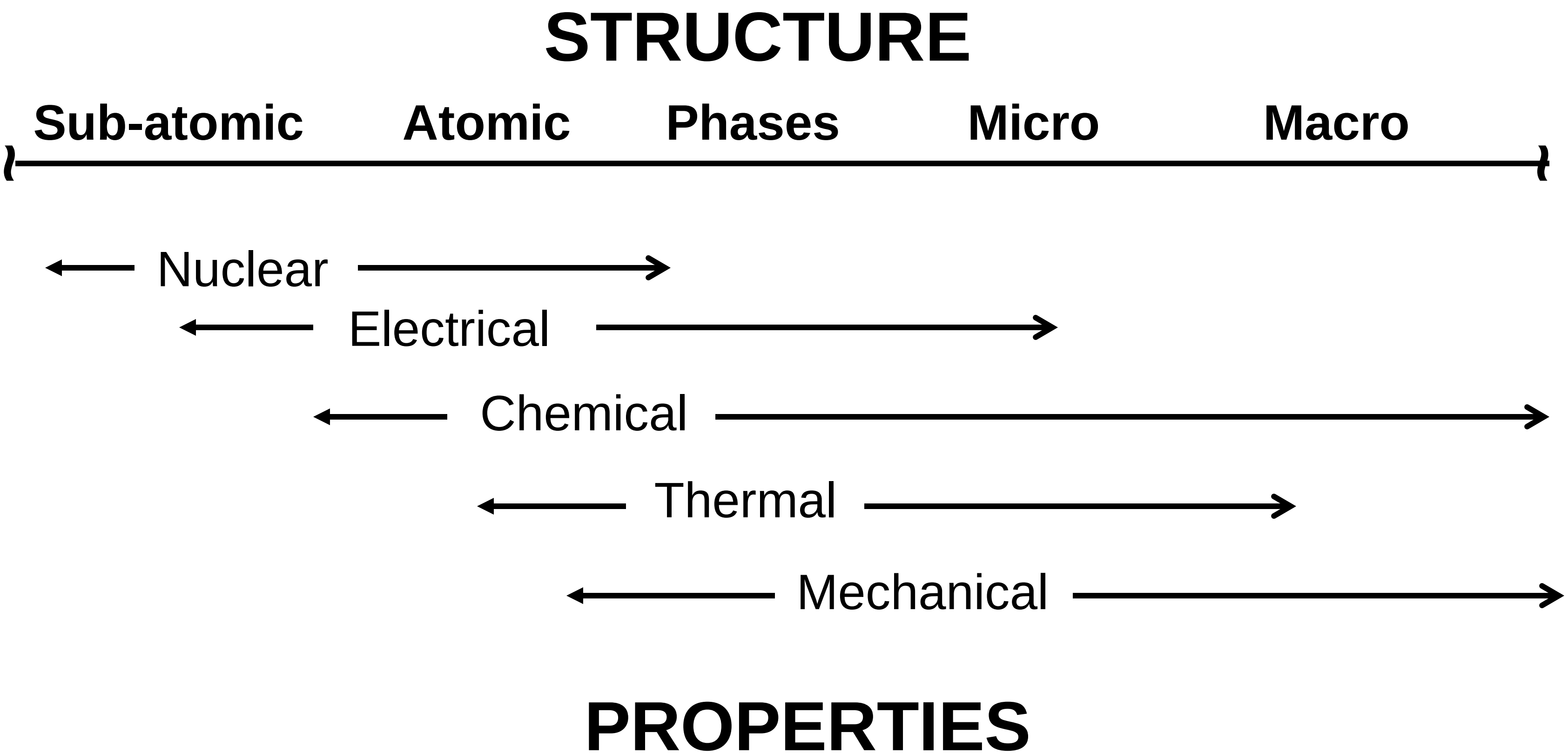




**Process Variations**
and/or defects such as:
Wrought vs. Cast Fabrication,
Casting Asymmetries and/or
Impurities and Inclusions
**lead to structural variations**.

**Structural Variations**
induced by environmental factors and/or "aging" such as:
Alloy Instability,
Self-Irradiation Damage,
Oxidation and Corrosion,
Fatigue and Fracture
**lead to properties variations**.

**Variations** (intentional or not) propagate through these casual relationships and must be understood to effectively manage **impact** to **performance uncertainty**.

# The General Relationship of Material Structure Size in Determining Various Properties



# Liquid Nuclear Fuels Data

LA-2358
CHEMISTRY--GENERAL
(TID-4500, 15th Ed.)

LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

REPORT WRITTEN: May 1959

THE DENSITY OF LIQUID PLUTONIUM METAL

by

C. E. Olsen, T. A. Sandenaw, and C. C. Herrick

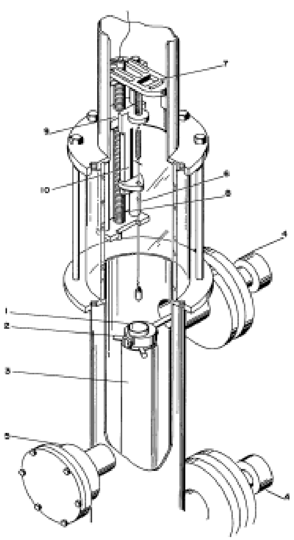


Fig. 1. Top of furnace and measuring apparatus.

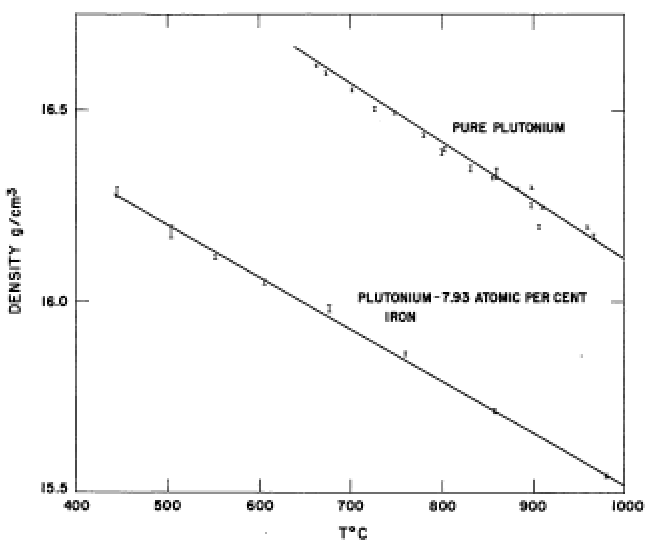



Fig. 2. Density vs temperature of plutonium-iron alloy.

THE JOURNAL OF CHEMICAL PHYSICS VOLUME 48, NUMBER 7 1 APRIL 1968

## Fluid Flow of Liquid Plutonium Alloys in an Oscillating-Cup Viscosimeter

L. J. Wittenberg and D. Ofte*
*Monsanto Research Corporation, Mound Laboratory,† Miamisburg, Ohio*
AND
C. F. Curtiss
*Theoretical Chemistry Institute, University of Wisconsin, Madison, Wisconsin*
(Received 18 January 1967)

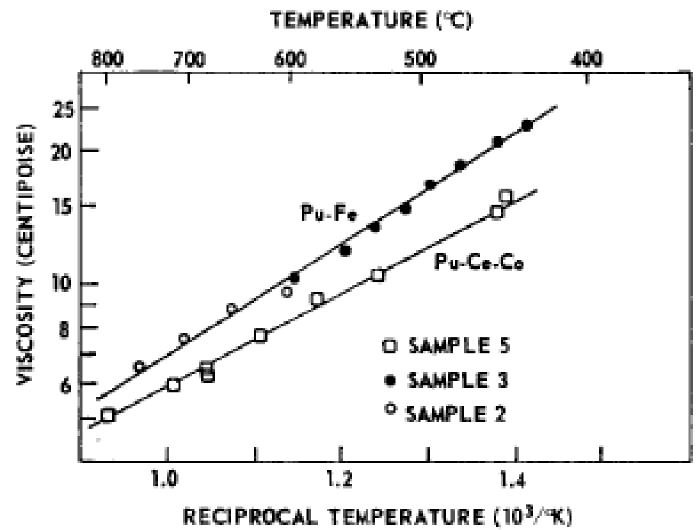



Fig. 6. Logarithm of viscosity as a function of reciprocal temperature for plutonium–iron and plutonium–cerium–cobalt alloys.

THE JOURNAL OF CHEMICAL PHYSICS VOLUME 56, NUMBER 9 1 MAY 1972

# Volume Contraction During Melting; Emphasis on Lanthanide and Actinide Metals

LAYTON J. WITTENBERG AND ROBERT DEWITT
*Mound Laboratory,* Monsanto Research Corporation, Miamisburg, Ohio 45342*

(Received 4 November 1971)

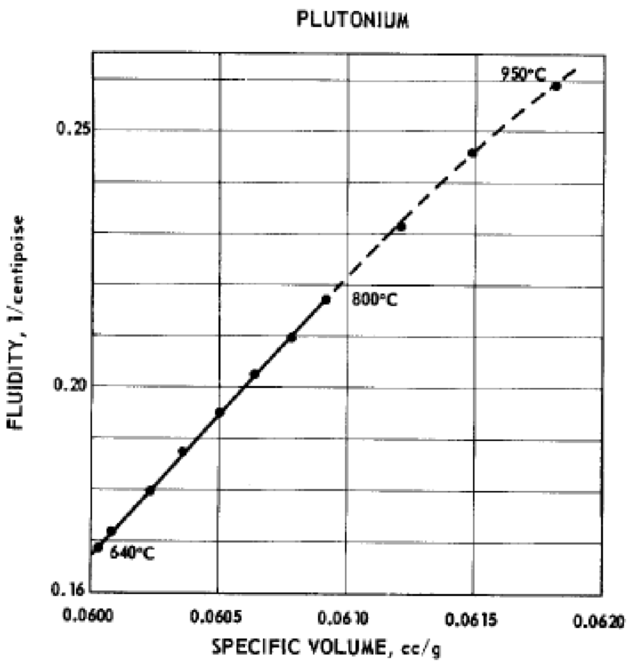



FIG. 2. Fluidity as a function of specific volume for liquid plutonium.

$$\eta^{-1}=(V_l-c)/B=(V_l/B)-(c/B).$$

$$\Delta V_f=(V_l-c)$$

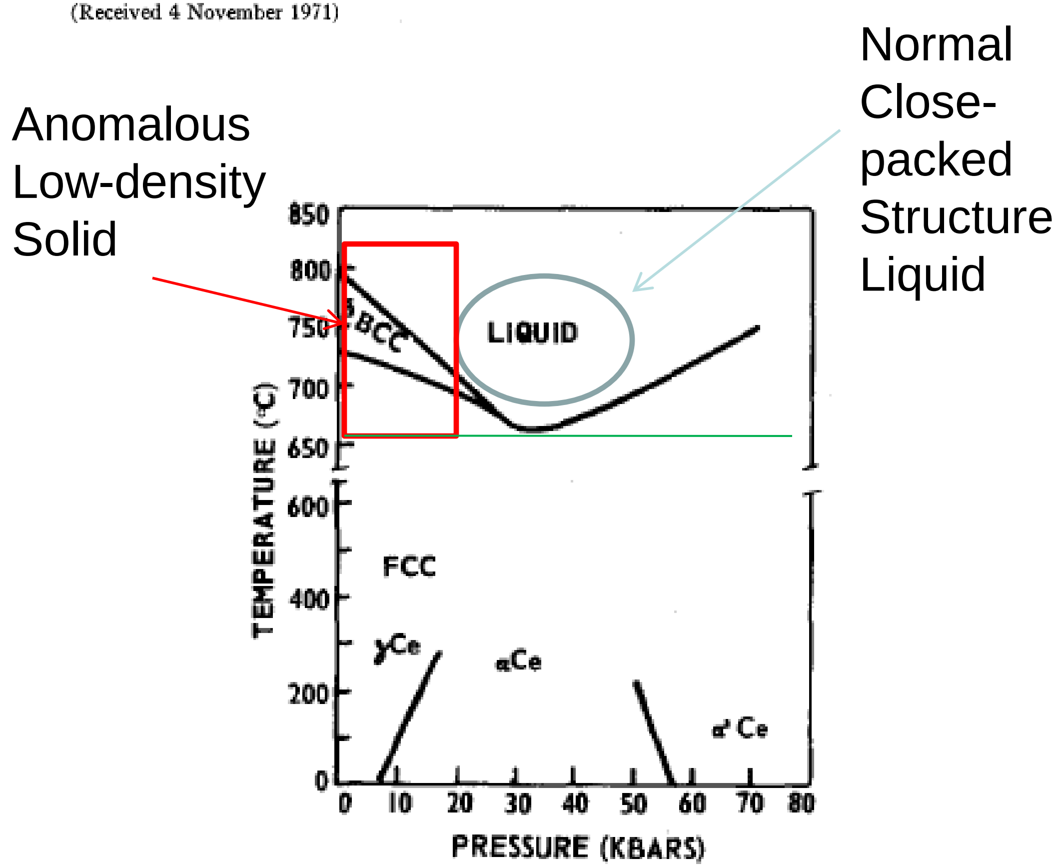



FIG. 6. Phase diagram of cerium (Ref. 16).

$$dT/dP=\Delta V_f/\Delta S.$$

# Plutonium Applications: MOX Fuels

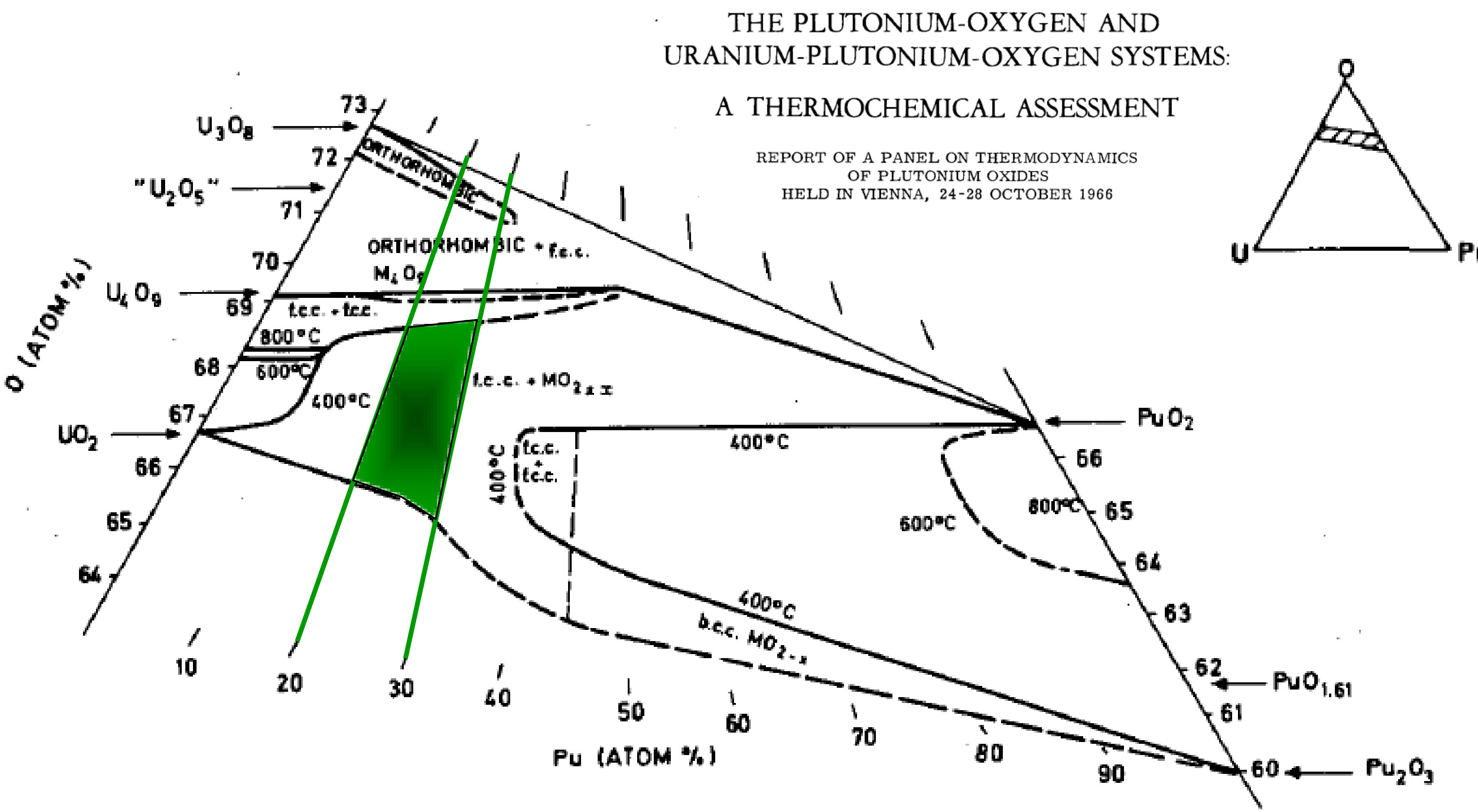
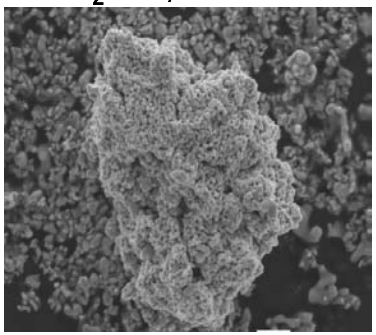


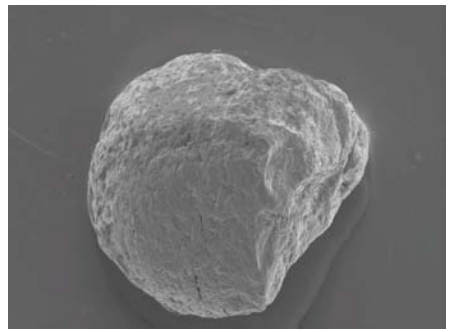

FIG. 13. U-Pu-O ternary section at 400, 600 and 800 °C.

# MAMOX: Precursor Oxide Particle Morphology and Fuels Microstructure

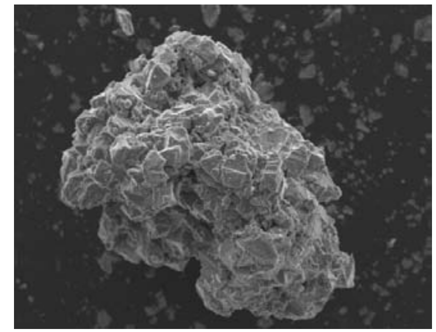
**$DUO_2$ 11,000x**



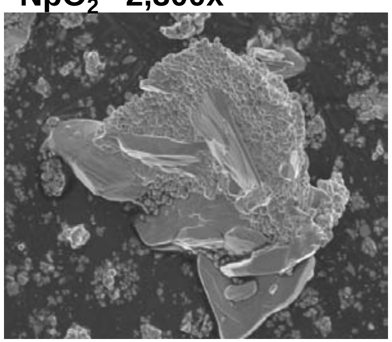
**$HEUO_2$ 1,400x**



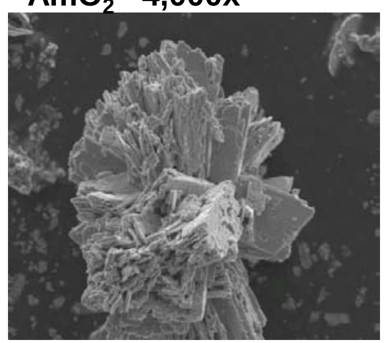
**$PuO_2$ 3,500x**



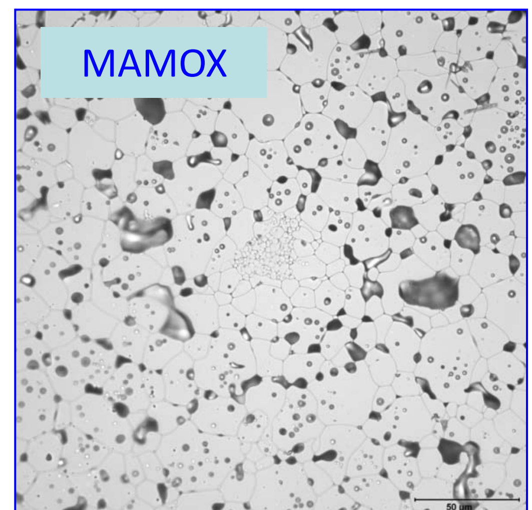
**$NpO_2$ 2,300x**



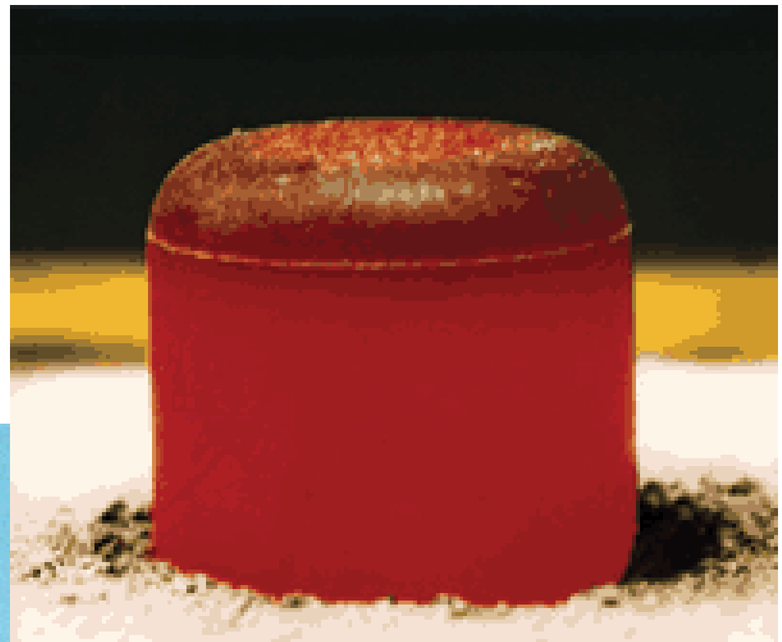
**$AmO_2$ 4,000x**

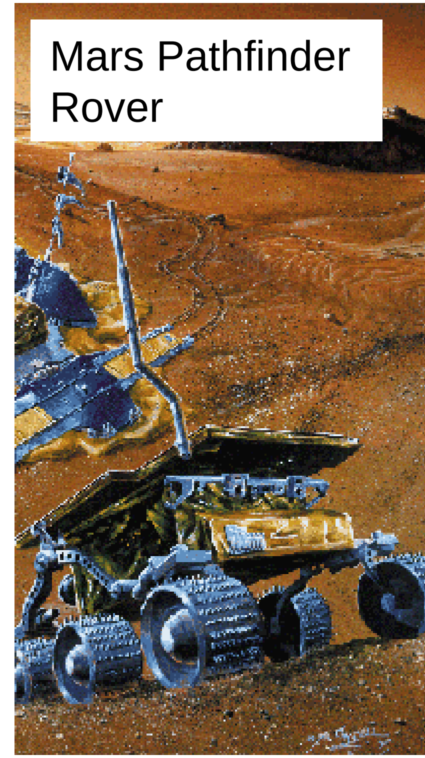


Pressing and Sintering



## Encapsulation of $Pu^{238}$ Oxide Heat Sources for NASA space missions





Mars Pathfinder Rover

**Radioisotope Thermoelectric Generator**

$Pu^{238}$ Oxide Energy Output: 0.54 watts/gram

Heat Source + Thermocouple = Electricity

Sebeck Effect: $\Delta V = \alpha \Delta T$

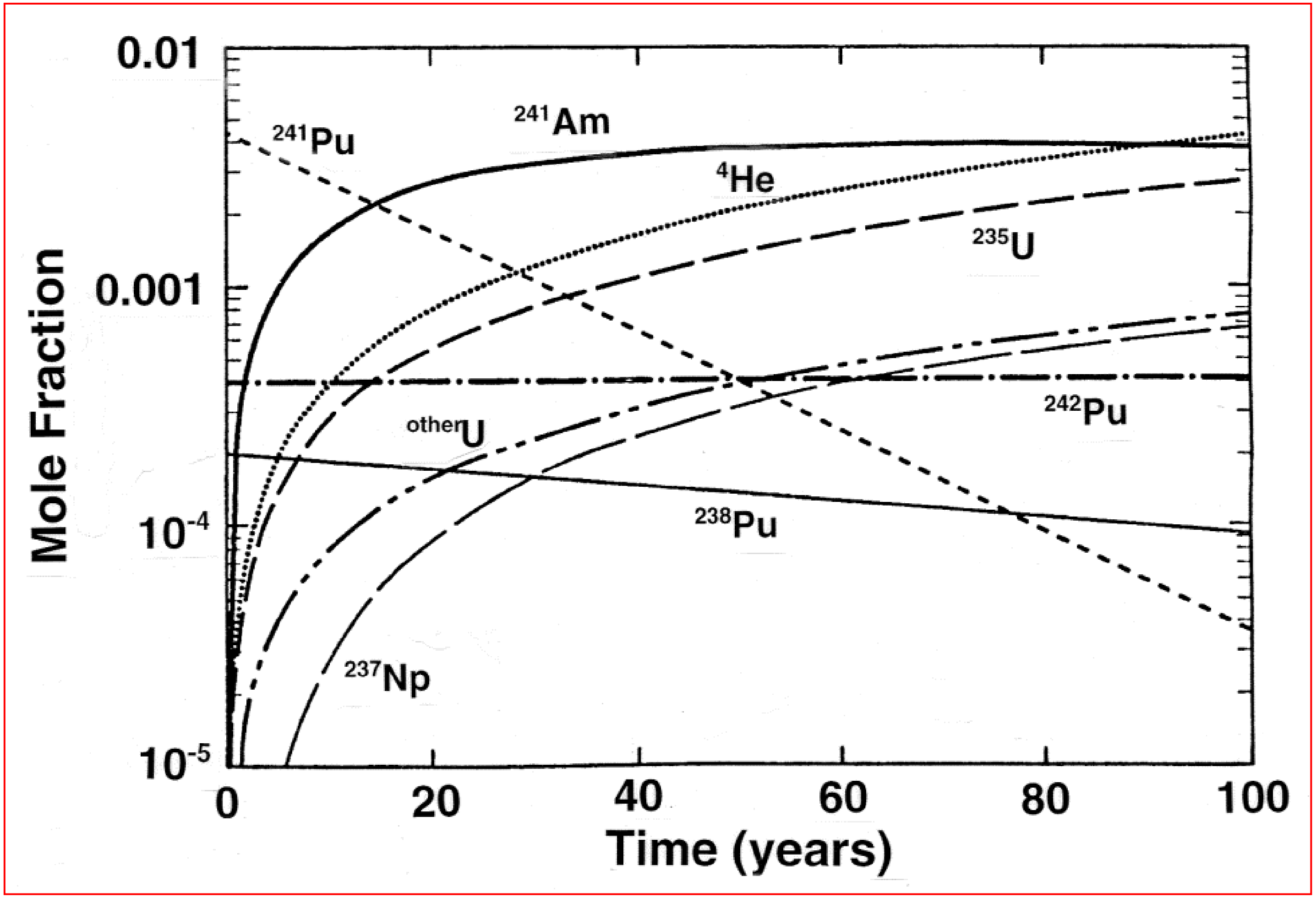
# Pu Self-Irradiation and Induced Aging Effects

# Plutonium Isotopes, Half-Lives and Typical Materials

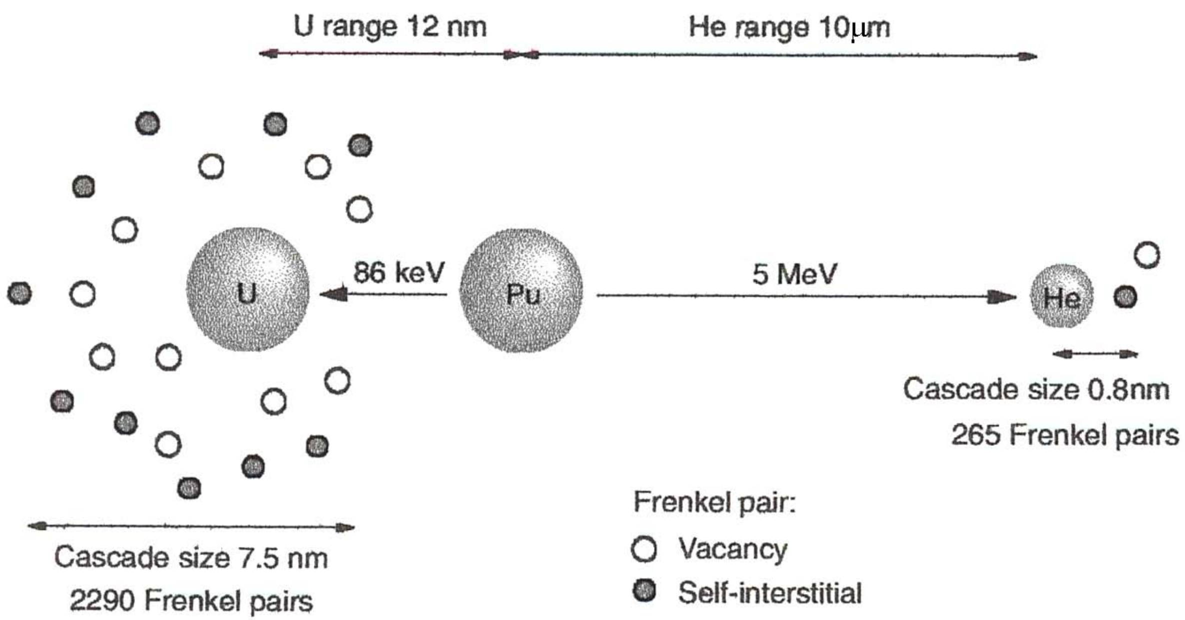
| Isotope Mass # | $T_{1/2}$ Half-life | Thermal neutron fission | Weapons Grade Plutonium (%) | Accelerated Aging (%) | Reactor Grade Plutonium (%) | Heat Source (%) |
|---|---|---|---|---|---|---|
| $Pu^{238}$ | 87.7 yrs | Probably | <0.05 | 7.5 | 1.5 | 90.0 |
| $Pu^{239}$ | 24,100 yrs | Yes | 86.1 | 93.6 | 58.1 | 9.1 |
| $Pu^{240}$ | 6,560 yrs | No | 6 | 6 | 24.1 | 0.6 |
| $Pu^{241}$ | 14.4 yrs | Yes | 0.4 | 0.4 | 11.4 | 0.03 |
| $Pu^{242}$ | $3.8 \times 10^5$ yrs | No | <0.05 | <0.05 | 4.9 | <0.01 |
| $Pu^{244}$ | $8.0 \times 10^7$ yrs | No | - | - | - | - |

From: Nuclides and Isotopes, 14th ed., General Electric Co., San Jose, CA, 1989.

# Daughter Product Ingrowth in Weapons Grade Pu



# Radioactive Decay of Plutonium




**Uranium:** Energy Deposition: Significant (85keV into 72,000 Unit Cells $\simeq$ 1.2meV/Å$^3$)
Residual Defect Structures: vacancies and interstitials
Inclusion Phases?: U complexes, Solute-Solvent Complexes (δ-phase alloys)

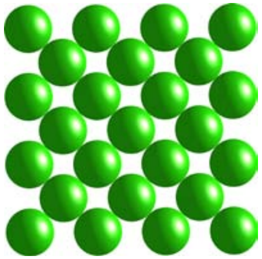
**Alpha Particle:** Energy Deposition: Minimal (5Mev into 40x10$^{12}$ Unit Cells $\simeq$ 1.3neV/Å$^3$);
Residual Defect Structures: not likely
Inclusion Phases: He Bubbles

# Perspective: Atoms to Bulk

| Relative Dimensions | | Type of Defect |
|---|---|---|
| 0.5 - 3 Å | Atom | **Electron** <br> **$p^+$, $n^-$** |
| $3^+$ - 5 Å | Unit Cell | **Point** <br> **Vacancy** |
| 10's - ~$10^4$ Å | Grains | **Line & Plane** <br> **Dislocations,** <br> **Faults,** <br> **Boundaries** |
| $10^2$ Å - very large | Bulk | **Volume** <br> **Voids,** <br> **Bubbles,** <br> **Inclusions** |
| | Process | **Flaws, "Cracks"** |

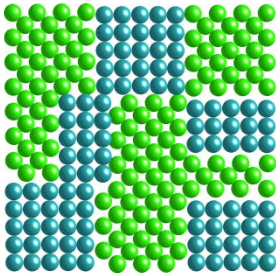
# Plutonium Aging: Length Scales and Properties

Atomic scale ~ 10 Å



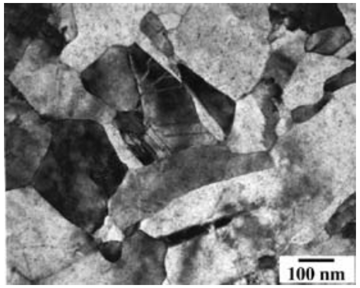
atomic structure

Nanoscale ~ 100Å



nano structure

Microscale ~ 100µ




bulk properties

Macroscale ~ 100cm

component processes

Fundamental structure of homogeneous materials

- Ga Distribution
- Impurities/Inclusions
- Lattice Constants
- Local Micro-structure
- Defect Structure
- Self-irradiation Damage
- Phase Stability
- Ga, Pu diffusion

Bulk properties of average structures, and heterogeneous materials

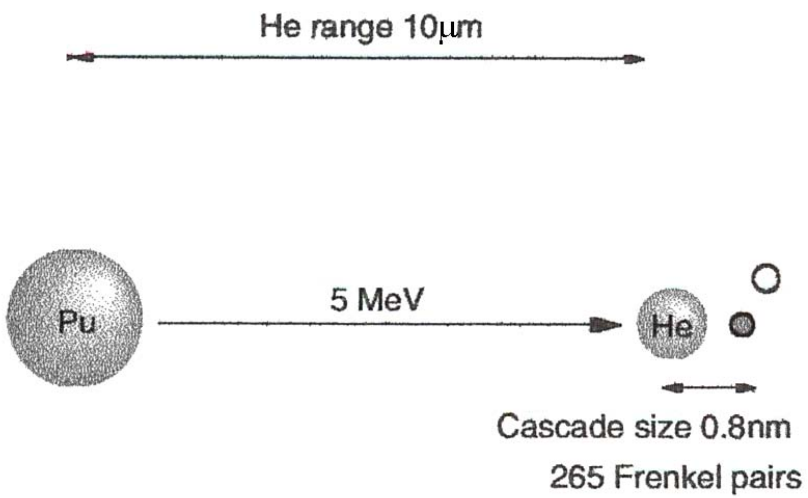
- lattice damage
- void swelling / He ingrowth
- He bubble formation
- Ga distribution "Coring"
- elastic properties
- density changes
- grain size
- dislocation structure

Controlling effects of heterogeneities, process coupling (chem, phys, mech)

- mechanical behavior
- dynamic properties
- stress-strain response
- strength, embrittlement
- weld stability
- corrosion behavior
- spall strength
- dimensional stability

# Effects of Alpha Particle Decay Branch

Nanoscale:
- Atomic He insoluble → He atoms coalesce → bubble nucleation and formation; and
- Local heating/damage from U-decay maintains some He in solution.




Microscale:
- Bubbles coalesce at grain boundaries (denuded region); and
- Nonequilibrium bubble growth and coalescence at temperatures greater than 500K.

Macroscale:
- Linear volume swelling with age;
- Volumetric expansion with bubble growth and coalescence ; and
- Bubbles introduce changes in thermophysical properties.

# Helium Bubbles in Aged δ-Pu Plutonium

## Characterization and modelling of helium bubbles in self-irradiated plutonium alloys

A. J. SCHWARTZ*†, M. A. WALL†, T. G. ZOCCO‡
and W. G. WOLFER†

†Lawrence Livermore National Laboratory, Livermore, CA 94550, USA
‡Los Alamos National Laboratory, Los Alamos, NM 87545, USA

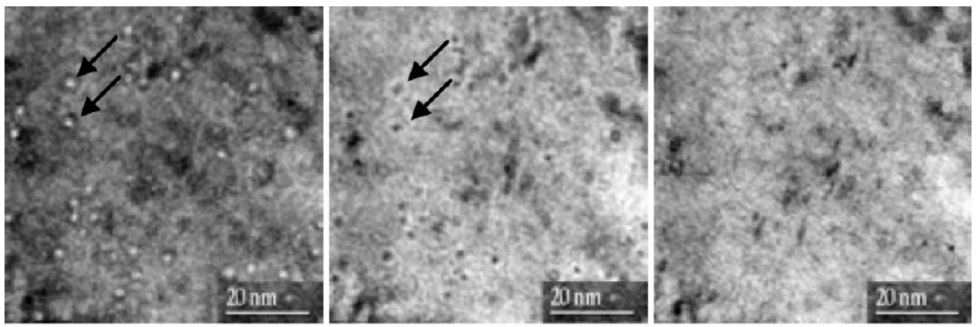



Figure 1. TEM images of 42-year-old Pu alloy. (a) The −1.4 µm under-focus bright-field TEM micrograph shows a high number density of very small helium bubbles as a dark fringe surrounding a light dot. (b) The + 1.4 µm over-focus image reveals the bubbles as light fringes surrounding a dark dot. (c) The in-focus image does not reveal the presence of bubbles due to the absence of a strain field.

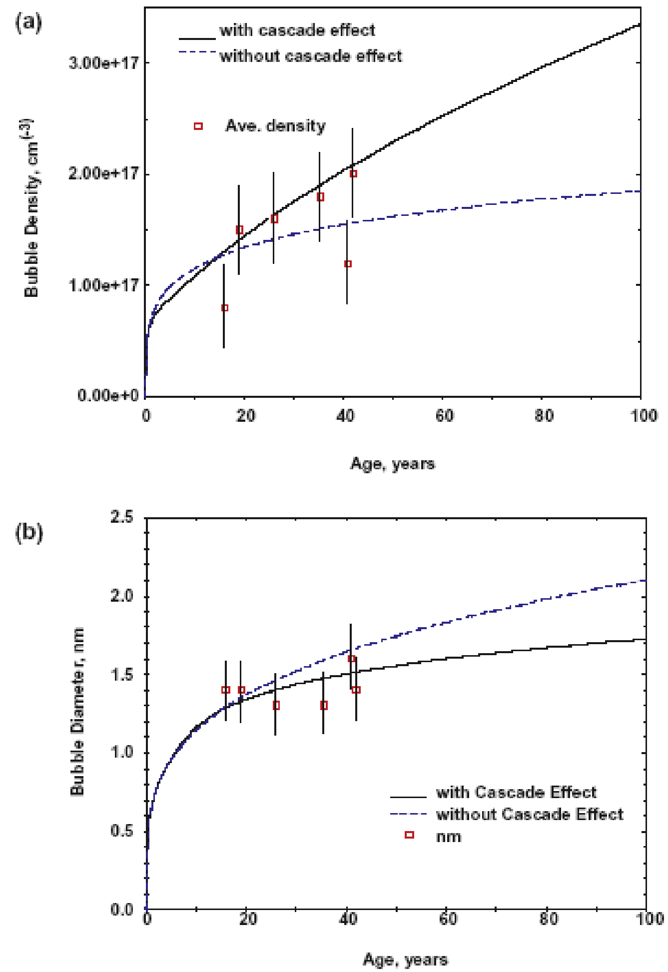
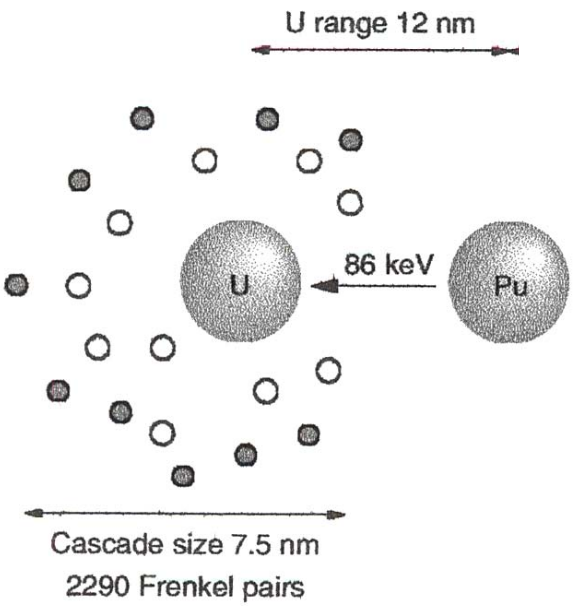



Figure 6. (a) Predicted helium bubble density and (b) average bubble diameter as a function of the plutonium age or the helium content (411 ppm He is generated in 10 years).

# Effects of Uranium Decay Branch

<u>Nanoscale:</u>

- Local "defects" or local ordering;
- Defect concentration saturates to a value proportional to alloy solute concentration → defect structure likely involves solute atoms;
- Defect distorts/strains local lattice; and
- Local heating/damage from U-decay anneals out some defects.



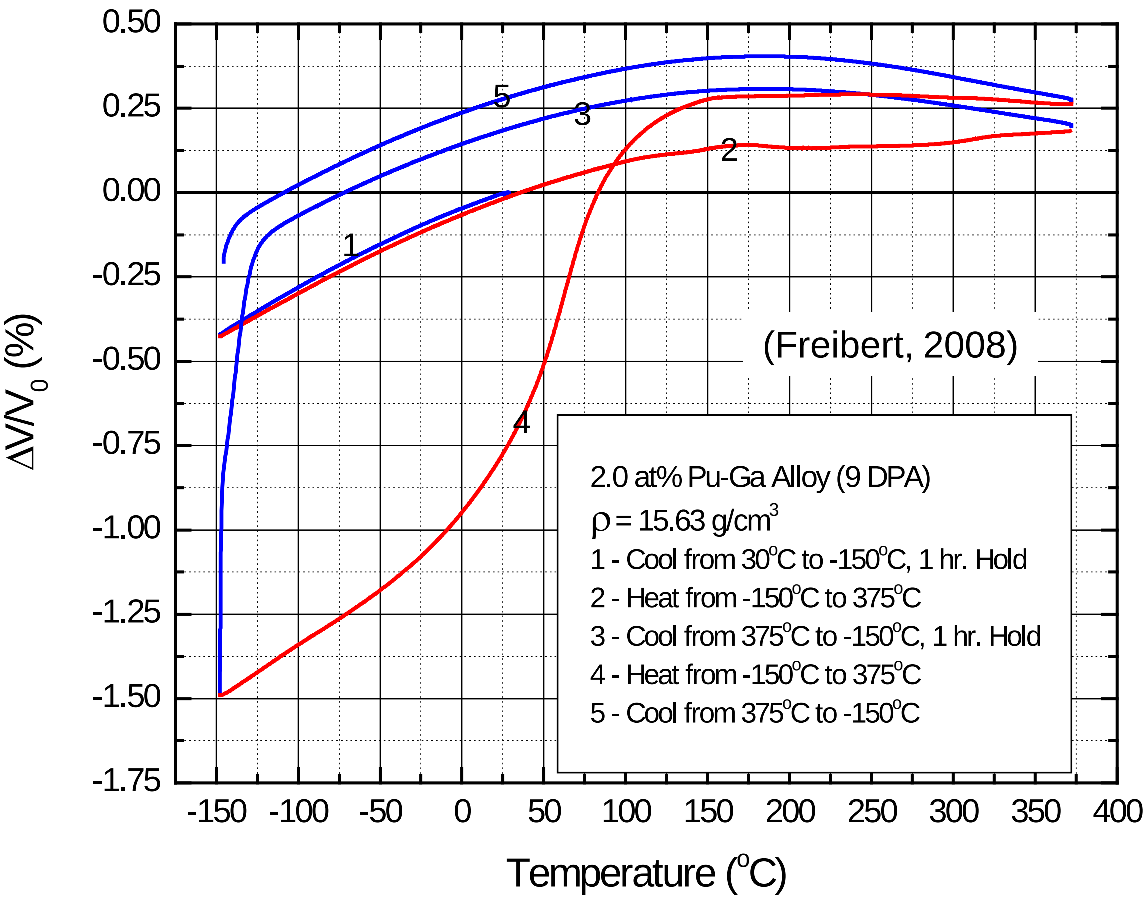

<u>Microscale:</u>

- Defects pin dislocations; and
- Defect generated strain field impedes δ→α' transformation.

<u>Macroscale:</u>

- Volume swelling from damage to point of saturation;
- Aging related mechanism increases yeild strength and removes strain rate dependence of flow stress; and
- Damage introduces transient changes in elastic moduli and other thermophysical properties.

## Defects Strain Lattice and Suppress Martensite Transformed Volume: Thermal Expansion of 7.5% $^{238}$Pu Alloy at 9 DPA (Equivalent 90 Yrs.)




9DPA of accumulated self-irradiation damage totally suppresses the δ → α'.

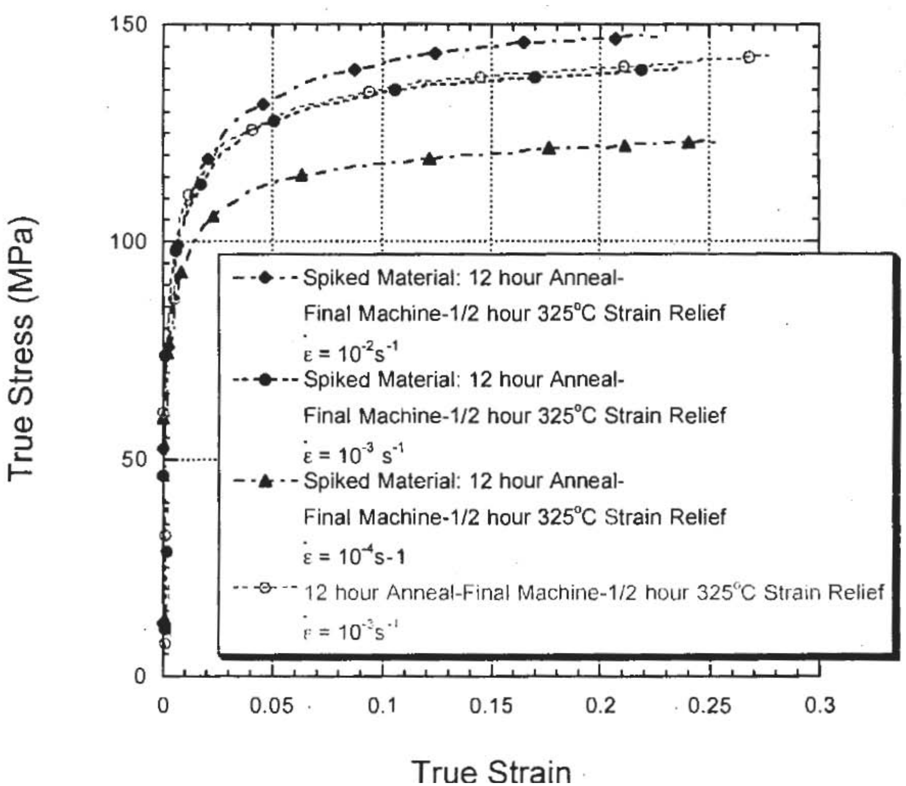
After damage anneals (T>150°C), δ → α' occurs in agreement with 0.6 w/o Ga alloy (Hecker, 2001): Transformation Onset: -130 °C.

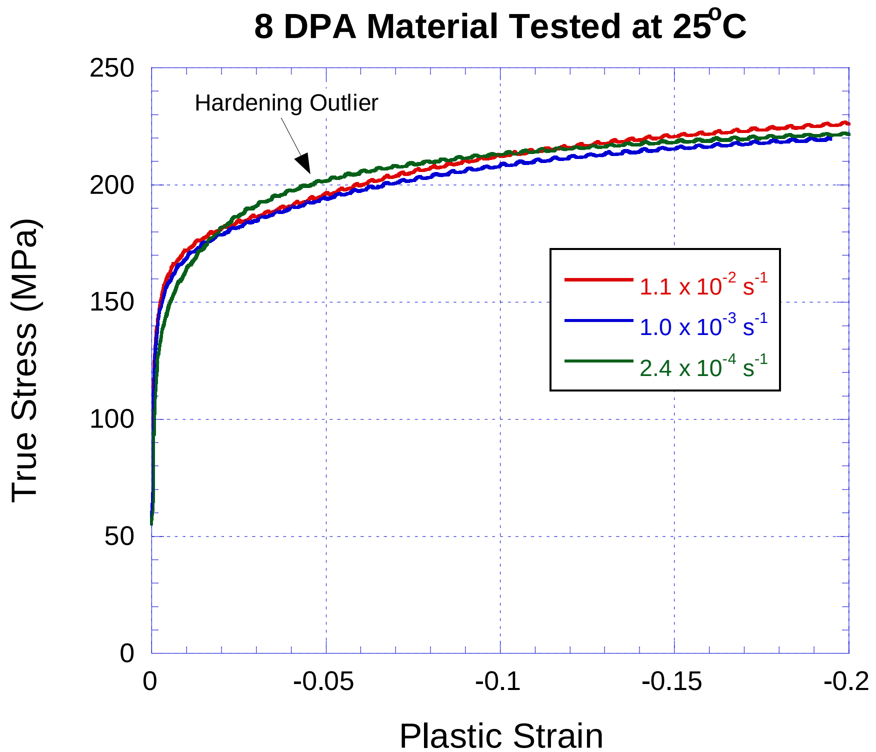
Full reversion (α' → δ) occurs from -150 to 150 °C.

Later thermal cycling shows:

- thermally induced swelling due to He bubble growth on heating; but
- typical δ-phase thermal expansion on cooling.

# Self-Irradiation Damage Provides Strengthening Mechanism



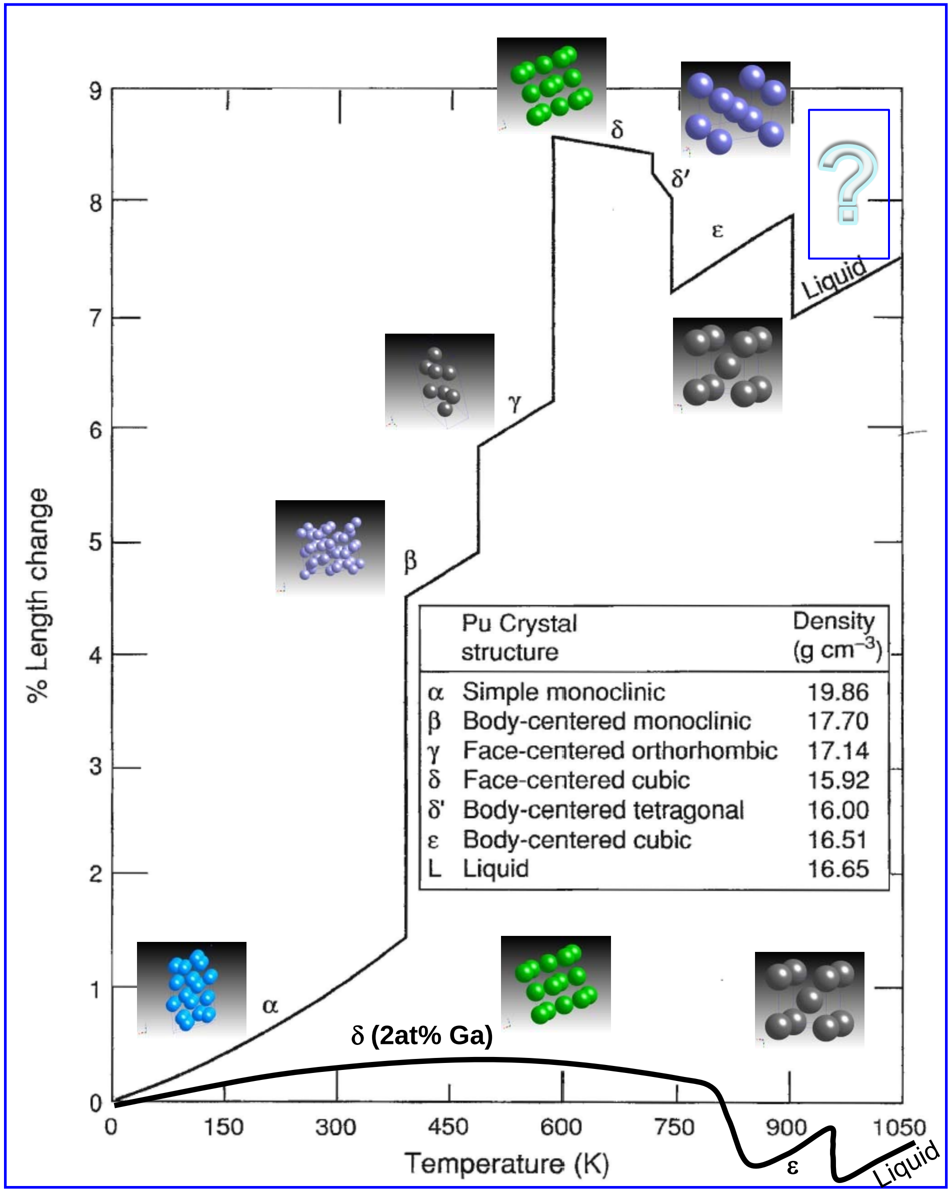




Damage (defects) likely acts to pin dislocations strengthening material under compressive load and dominating strain rate strength dependence. These data correlate with data from shear modulus changes (RUS) and micro-hardness measurements.

# Unalloyed Plutonium Structural, Thermodynamic and Mechanical Properties

# Crystal Structure Data for Plutonium

| Phase | Stability Range ºC | Space Lattice and Space Group | Unit Cell Dimensions, A | Atoms per unit Cell | X-ray Density, $gm/cm^3$ |
|---|---|---|---|---|---|
| α | Below ~115 | Simple monoclinic<br>*P*2$_1$/*m* | **@21 ºC:**<br>a= 6.183 ±0.001<br>b= 4.822 ±0.001<br>c= 10.963 ±0.001<br>β= 101.79º ±0.01º | 16 | 19.86 |
| β | ~115-~200 | Body-centered Monoclinic<br>*I*2/*m* | **@190 ºC:**<br>a= 9.284 ±0.003<br>b= 10.463 ±0.004<br>c= 7.859 ±0.003<br>β= 92.13º ±0.03º | 34 | 17.70 |
| γ | ~200-310 | Face-centered orthorhombic<br>*Fddd* | **@235 ºC:**<br>a= 3.159 ±0.001<br>b= 5.768 ±0.001<br>c= 10.162 ±0.002 | 8 | 17.14 |
| δ | 310-452 | Face-centered cubic, *Fm*3*m* | **@320 ºC:**<br>a= 4.6371 ±0.004 | 4 | 15.92 |
| δ' | 452-480 | Body-centered tetragonal<br>*I*4/*mmm* | **@465 ºC:**<br>a= 3.34 ±0.01<br>c= 4.44 ±0.04 | 2 | 16.00 |
| ε | 480-640 | Body-centered cubic, *Im*3*m* | **@490 ºC:**<br>a= 3.6361 ±0.004 | 2 | 16.51 |




# Plutonium: An Inherently Unstable Element

- **Phase Transformations**
  - 5 Solid-Solid Allotropic Transformations
  - Shear and Diffusion Driven
- **Thermodynamics**
  - Quantitative and Qualitative Character
- **Kinetics (Heating vs. Cooling)**
  - Rapid vs. Sluggish Atomic Movements
- **Ga as an Impurity**
  - Interstitial (Lattice Const. increase: α')
- **Ga Alloying**
  - Lowers δ-Pu Phase Free Energy and Stabilizes δ-Pu
  - Substitutional in δ-Pu (XAFS)
  - Alters Electronic Structure (TEC - → +)
  - Diffusional δ↔ε transformation
- **Impact of Microstructure and Impurities**
  - Grain size, Morphology, and Texture
  - $Pu_6Fe$ and other Inclusions
- **Anharmonic Effects**
  - Non-Debye Solid Behavior

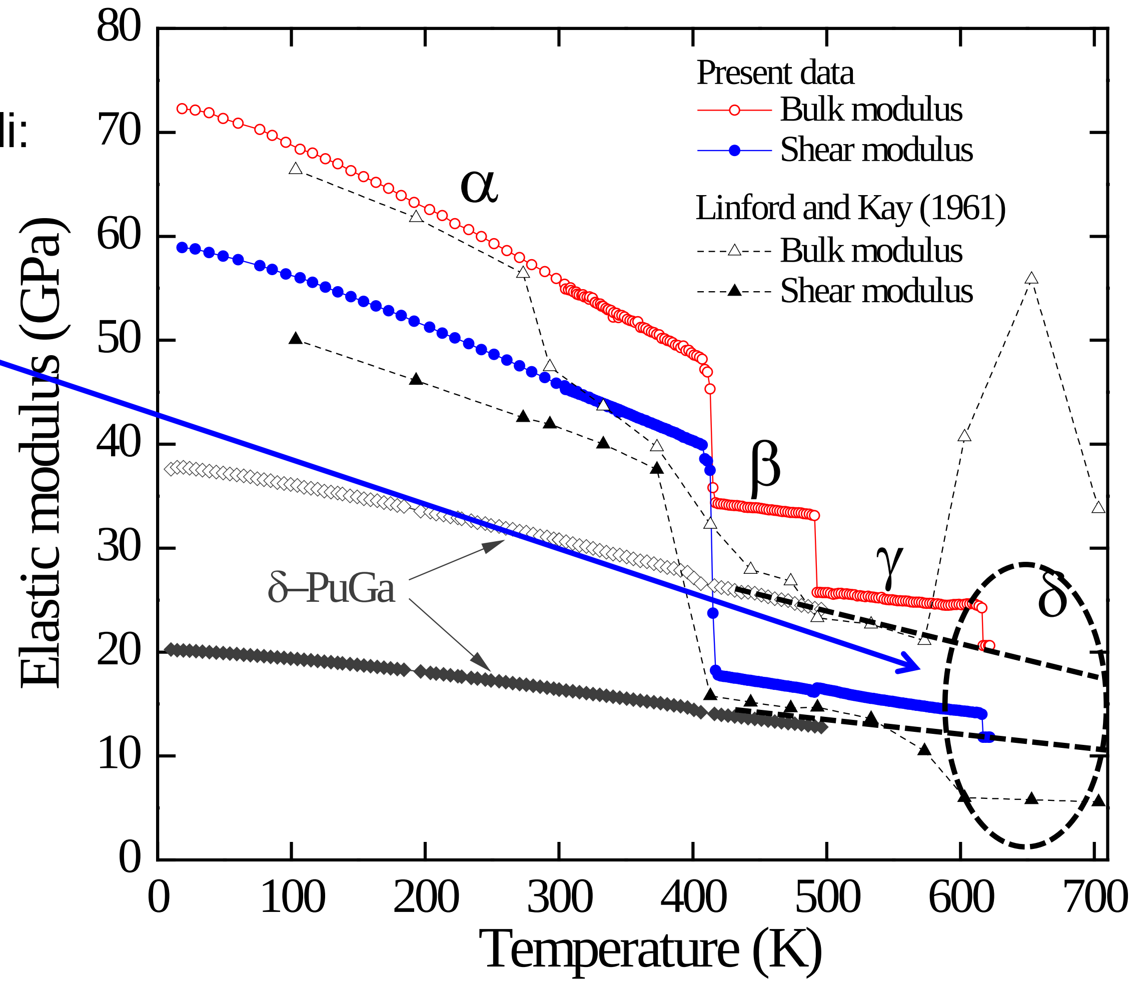
# Unalloyed δ-Pu and 2at% Ga stabilized δ-Pu are elastically similar!

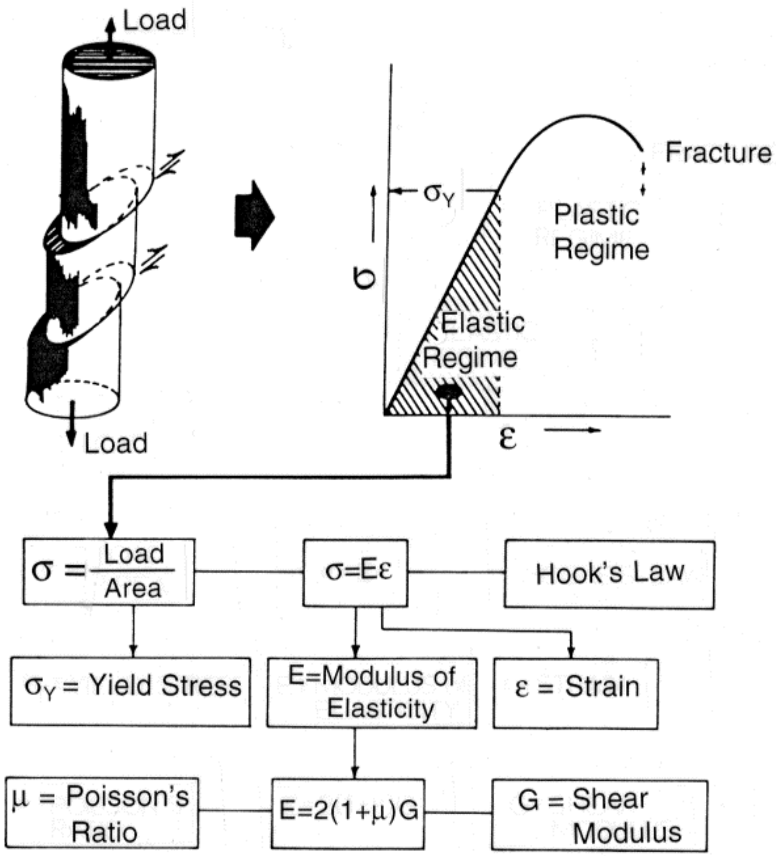
- Unalloyed and Ga alloyed δ-Pu exhibit same values of bulk and shear elastic moduli:

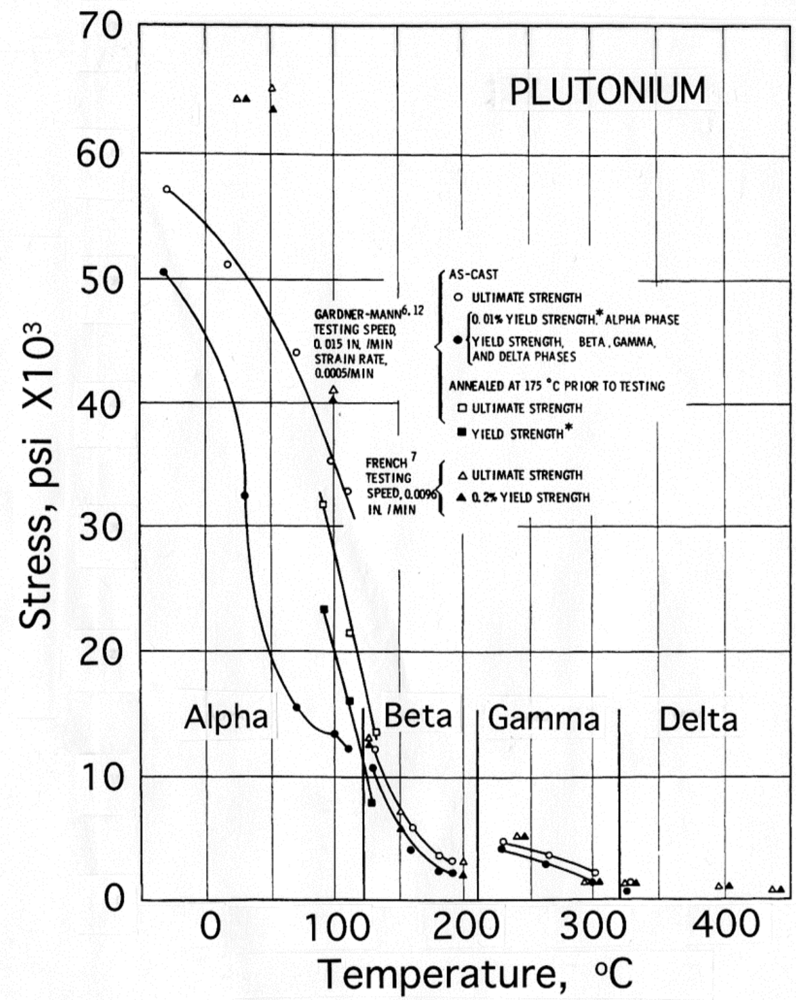
$$B_{\delta-Pu} = 20.6\ \text{GPa}$$
$$G_{\delta-Pu} = 11.8\ \text{GPa}$$
$$B^{Ext.}_{\delta-PuGa} = 22\ \text{GPa}$$
$$G^{Ext.}_{\delta-PuGa} = 12\ \text{GPa}$$

- α→β, β→γ, and γ→δ Pu transformation are continuous.

- β-Pu and γ-Pu exhibit the same shear modulus with a 30% variation in bulk modulus.




Load
Load
σ
$\sigma_Y$
ε
Fracture
Plastic Regime
Elastic Regime
$\sigma = \frac{\text{Load}}{\text{Area}}$
σ=Eε
Hook's Law
$\sigma_Y$ = Yield Stress
E=Modulus of Elasticity
ε = Strain
μ = Poisson's Ratio
E=2(1+μ)G
G = Shear Modulus


PLUTONIUM
Stress, psi X10³
Temperature, °C
70
60
50
40
30
20
10
0
0
100
200
300
400
Alpha
Beta
Gamma
Delta
GARDNER-MANN 6, 12 TESTING SPEED, 0.015 IN. /MIN STRAIN RATE, 0.0005/MIN
AS-CAST
ULTIMATE STRENGTH
0.01% YIELD STRENGTH,* ALPHA PHASE
YIELD STRENGTH, BETA, GAMMA, AND DELTA PHASES
ANNEALED AT 175 °C PRIOR TO TESTING
ULTIMATE STRENGTH
YIELD STRENGTH*
FRENCH 7 TESTING SPEED, 0.0096 IN. /MIN
ULTIMATE STRENGTH
0.2% YIELD STRENGTH

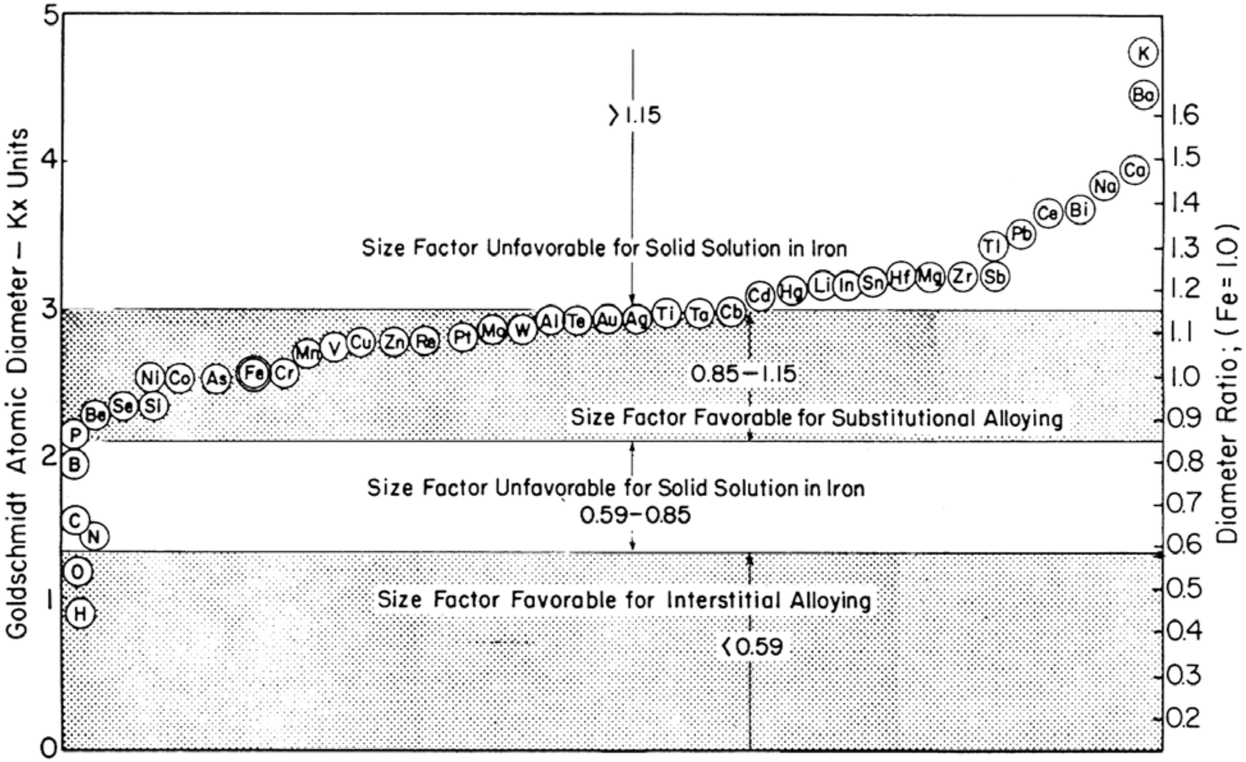
# Plutonium Alloys and Metallurgy

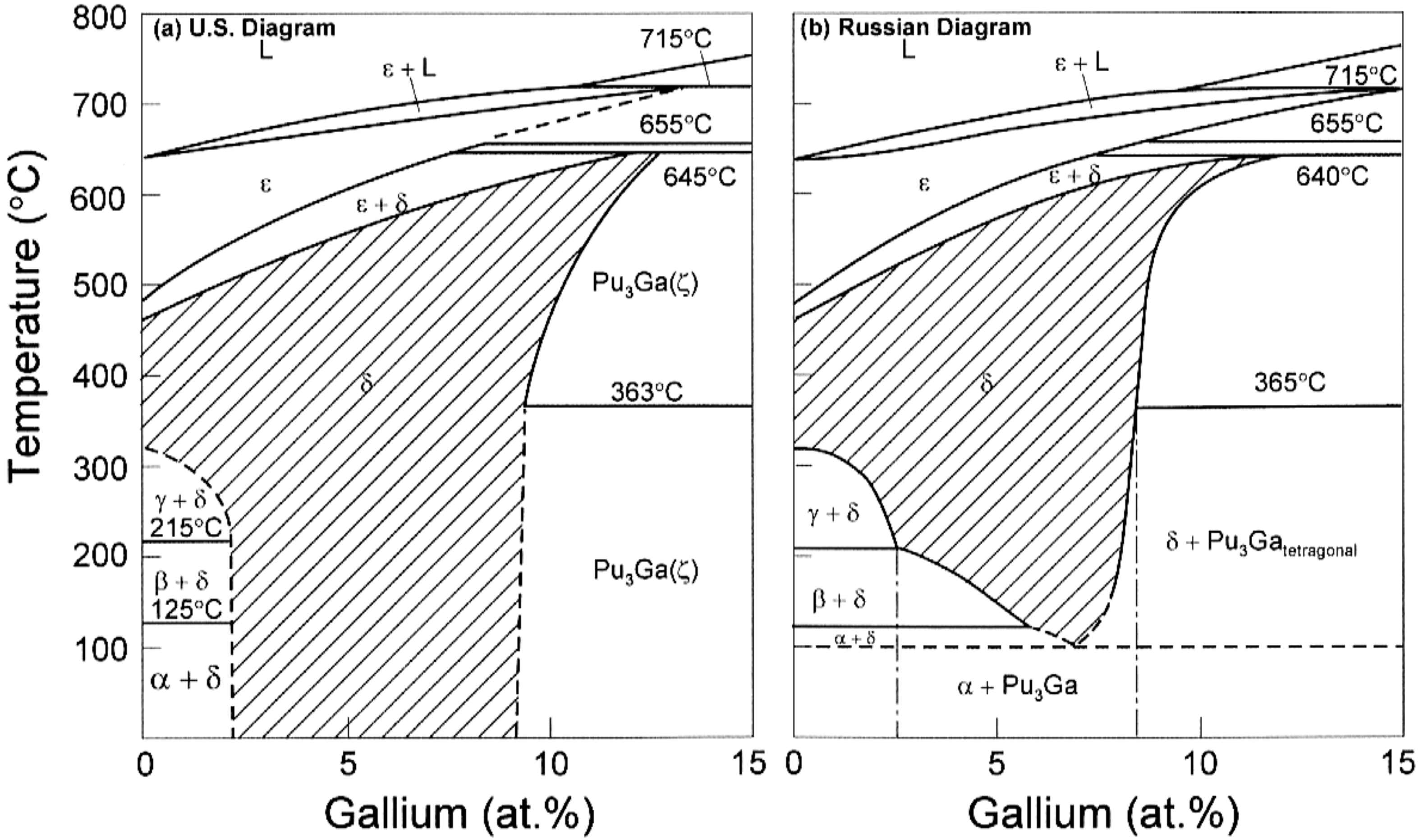
# Elements that Alloy with Plutonium

| Phase | | To R.T. | Not to R.T. (>1 wt. %) |
|---|---|---|---|
| α | | Np, Ru, Zr | |
| β | | | Np, U, Zr |
| γ | | | Np, Th, U, Zr |
| δ | | Al, Am, Ce, Ga, Sc | In, Np, Nd, Pm, Ru, Si, Sm, Th, Ti, U, Zn, Zr |
| δ′ | | | Am, Np |
| ε | | | Ag, Al, Am, Ce, Cu, Dy, Er, Ga, Gd, Ho, In, Lu, Nd, Ni, Np, Os, Pd, Pm, Pr, Pt, Rh, Ru, Sc, Si, Sm, Th, Ti, Tm, U, Zn, Zr |

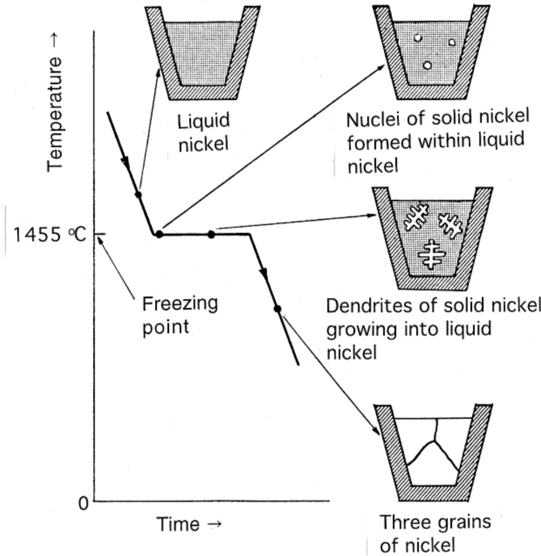
# Hume-Rothery Rules for Complete Solid Solubility and Alloying

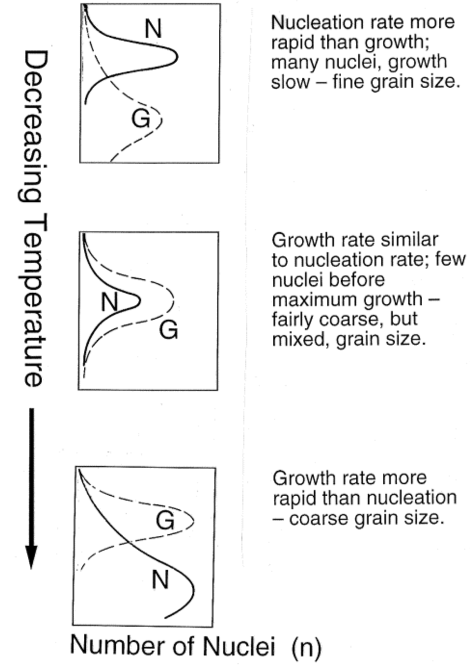
1. Must have the same crystal structure.
2. Less than ±15 % difference in atomic radii.
3. Same valence.
4. Similar electronegativity.

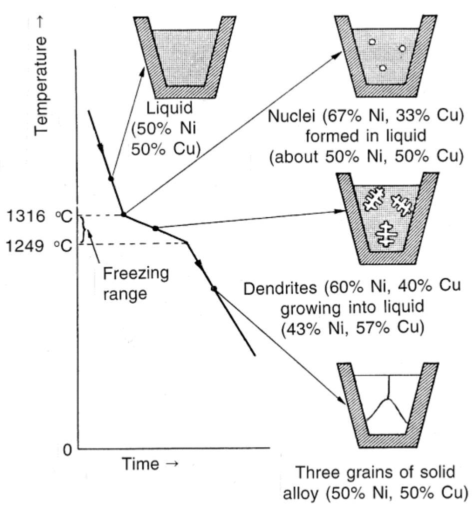


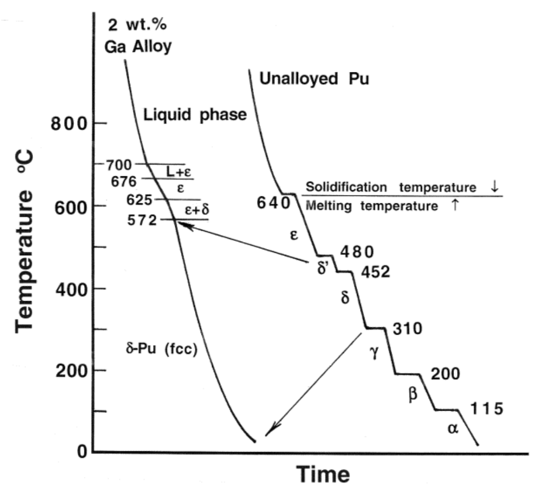


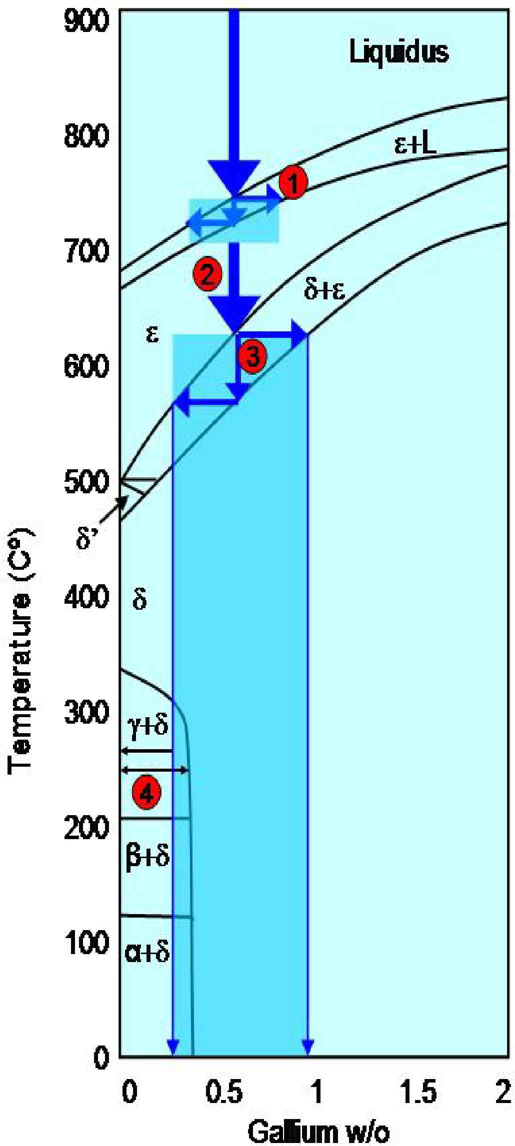
(a) U.S. Diagram
L
ε + L
715°C
655°C
645°C
ε
ε + δ
Pu3Ga(ζ)
δ
363°C
γ + δ
215°C
β + δ
125°C
α + δ
Pu3Ga(ζ)
(b) Russian Diagram
L
ε + L
715°C
655°C
640°C
ε
ε + δ
δ
365°C
γ + δ
δ + Pu3Ga tetragonal
β + δ
α + δ
α + Pu3Ga
Temperature (°C)
800
700
600
500
400
300
200
100
0
5
10
15
Gallium (at.%)


Temperature →
Liquid nickel
Nuclei of solid nickel formed within liquid nickel
1455 °C
Dendrites of solid nickel growing into liquid nickel
Freezing point
0
Time →
Three grains of nickel


Decreasing Temperature
N
G
Nucleation rate more rapid than growth; many nuclei, growth slow – fine grain size.
Growth rate similar to nucleation rate; few nuclei before maximum growth – fairly coarse, but mixed, grain size.
Growth rate more rapid than nucleation – coarse grain size.
Number of Nuclei (n)

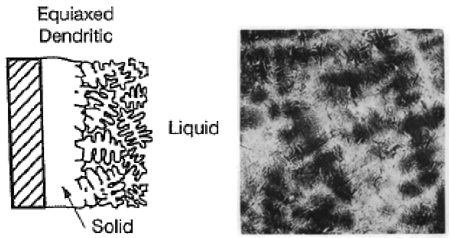

Temperature →
Liquid (50% Ni 50% Cu)
Nuclei (67% Ni, 33% Cu) formed in liquid (about 50% Ni, 50% Cu)
1316 °C
1249 °C
Freezing range
Dendrites (60% Ni, 40% Cu growing into liquid (43% Ni, 57% Cu)
0
Time →
Three grains of solid alloy (50% Ni, 50% Cu)


2 wt.% Ga Alloy
Unalloyed Pu
Liquid phase
Temperature °C
800
700
676
625
572
600
400
200
0
L+ε
ε
ε+δ
640
Solidification temperature ↓
Melting temperature ↑
ε
480
δ'
452
δ
310
γ
δ-Pu (fcc)
200
β
115
α
Time




# Casting Pu-Ga Alloys

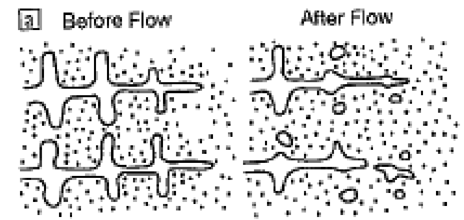
1



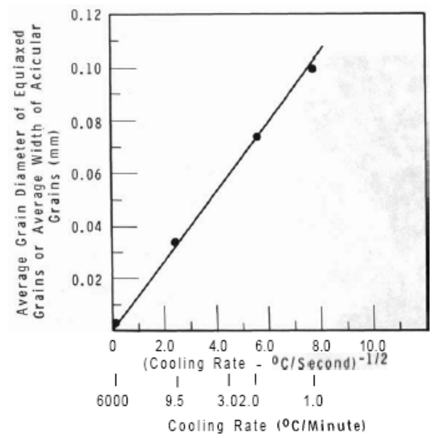

Solidification within ε+L phase field involves equiaxed dendrite formation initiated at the mold walls. Microsegregation of Ga or "coring" occurs.

2

Anisotropic negative thermal expansion and low yield strength in ε–phase results in plastic flow and dendrite breakage. Ga diffuses quickly due to high temperature and so reduces coring.




3




Microsegregation of Ga or "coring" occurs once again . Cooling rate through δ+ε phase field determines final cored grains.

4

Phase segregation occurs in Pu rich regions. Upon cooling, α-phase regions contain soluble Ga. Both α-phase and δ–phase regions remain metastable and under extreme residual stress due to density and thermal expansion differences of phases.

# As-Cast Microstructure Shows Dark High-Gallium δ Cores Surrounded by Light Low-Gallium α Matrix

# Theory

Modeling of Structural and Compositional Homogenization of Plutonium-1 Weight Percent Gallium Alloys

JEREMY N. MITCHELL, FRANK E. GIBBS, THOMAS G. ZOCCO, and RAMIRO A. PEREYRA

METALLURGICAL AND MATERIALS TRANSACTIONS A

VOLUME 32A, MARCH 2001—649

Homogenization is dictated by Fick's Second Law:

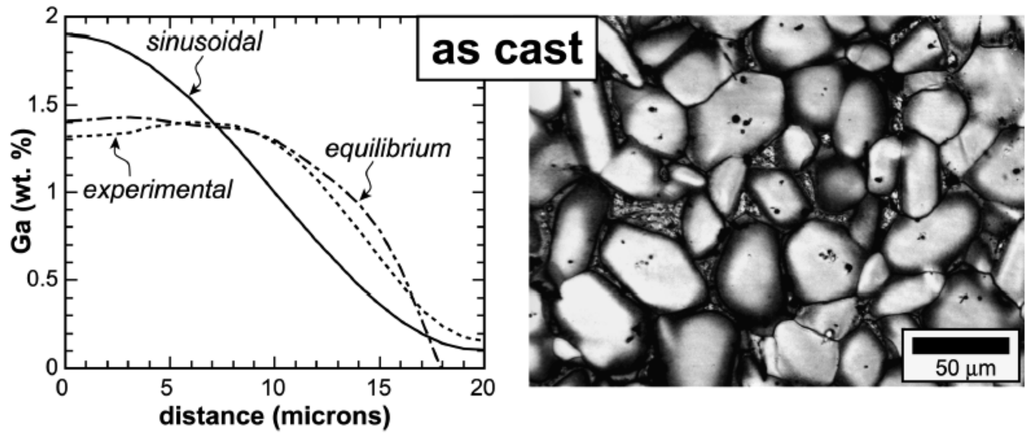
$$\frac{\partial C(x,t)}{\partial t} = D\frac{\partial^2 C(x,t)}{\partial x^2}$$

where D [ $\mathrm{cm}^2/s$ ] is the diffusivity

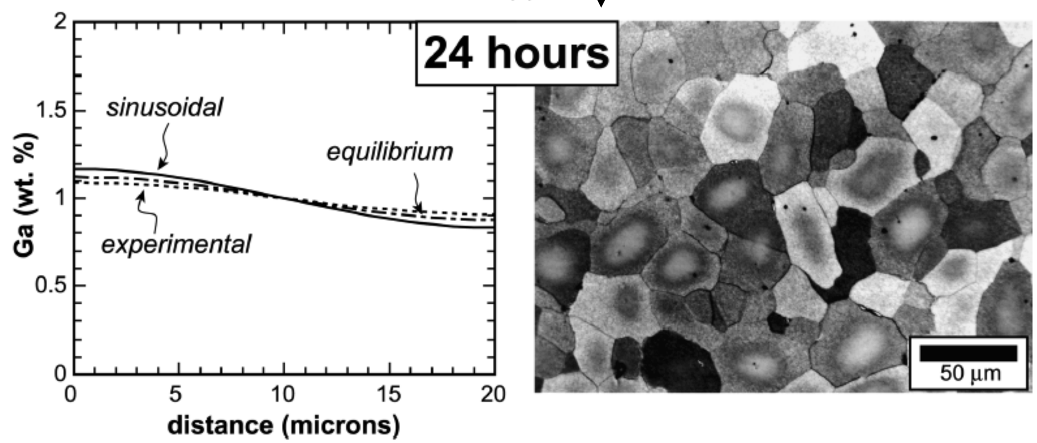
Diffusivity of Ga in Pu = ?

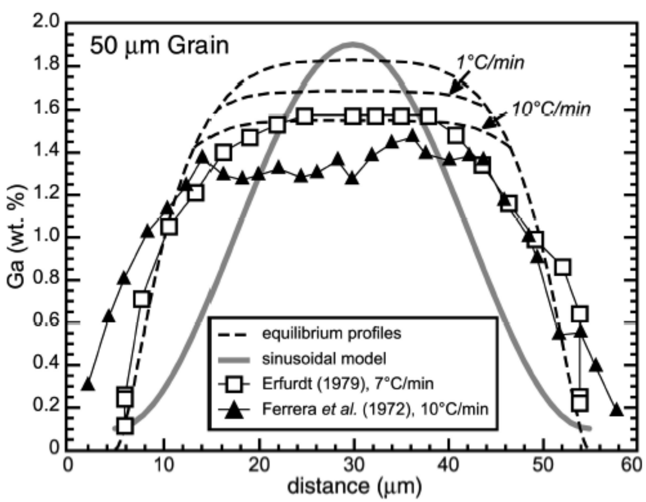
$$C(x,t) = C_0 \sin(\pi x/l)\exp(-t/\tau)$$

where $\tau(t) = l^2/\pi^2 D$.

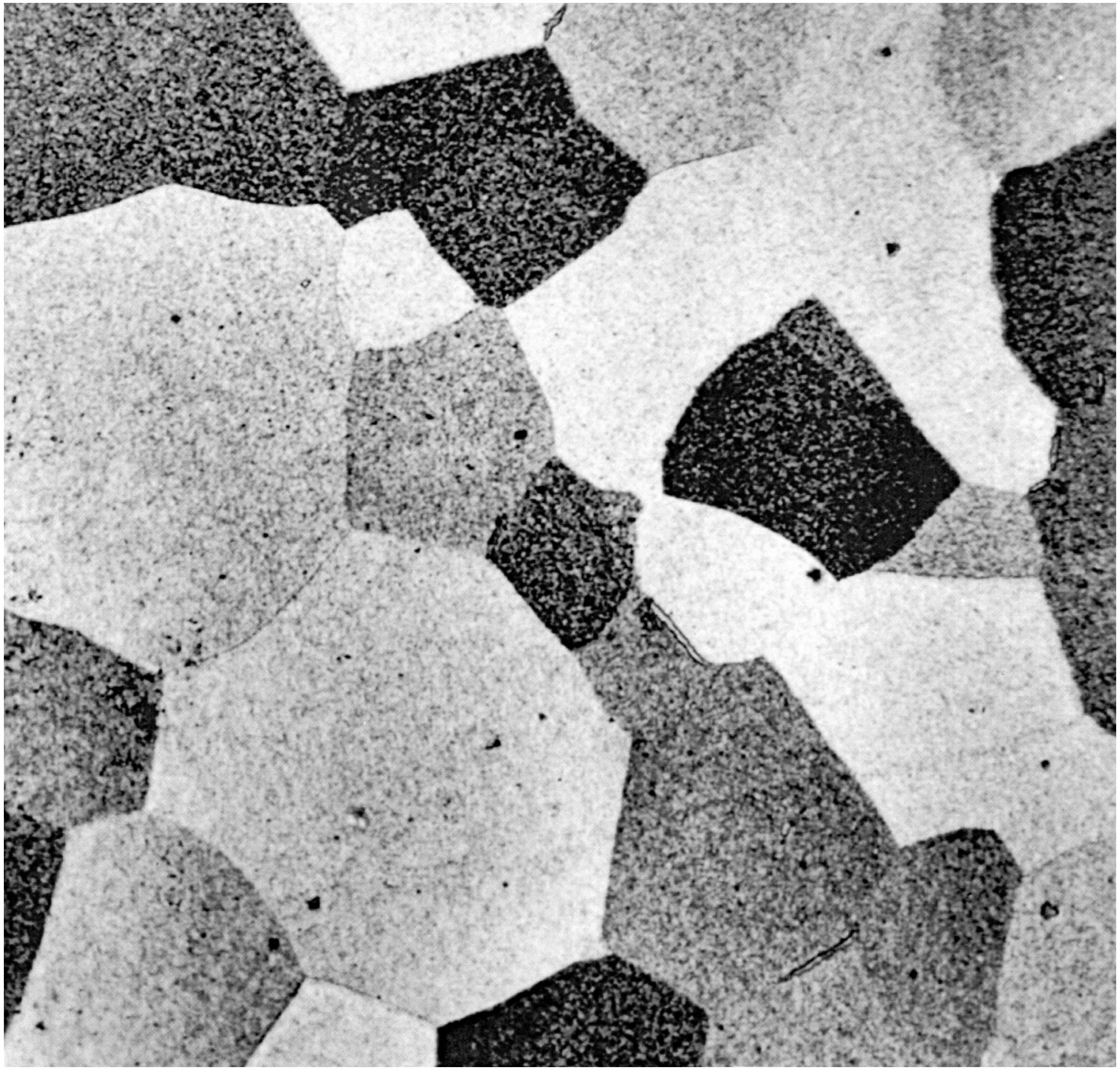


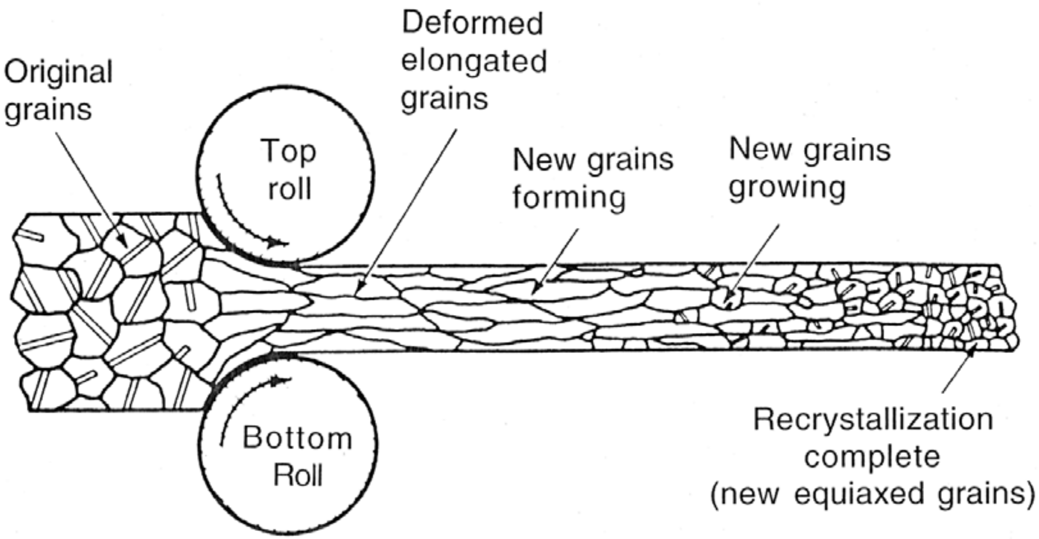

Homogenization at 450$^0$C

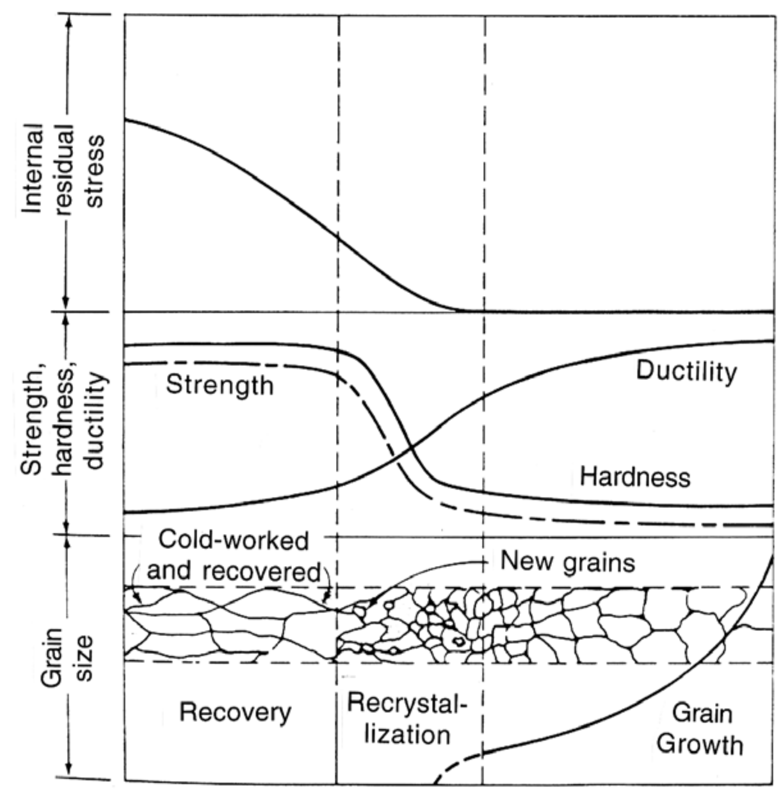


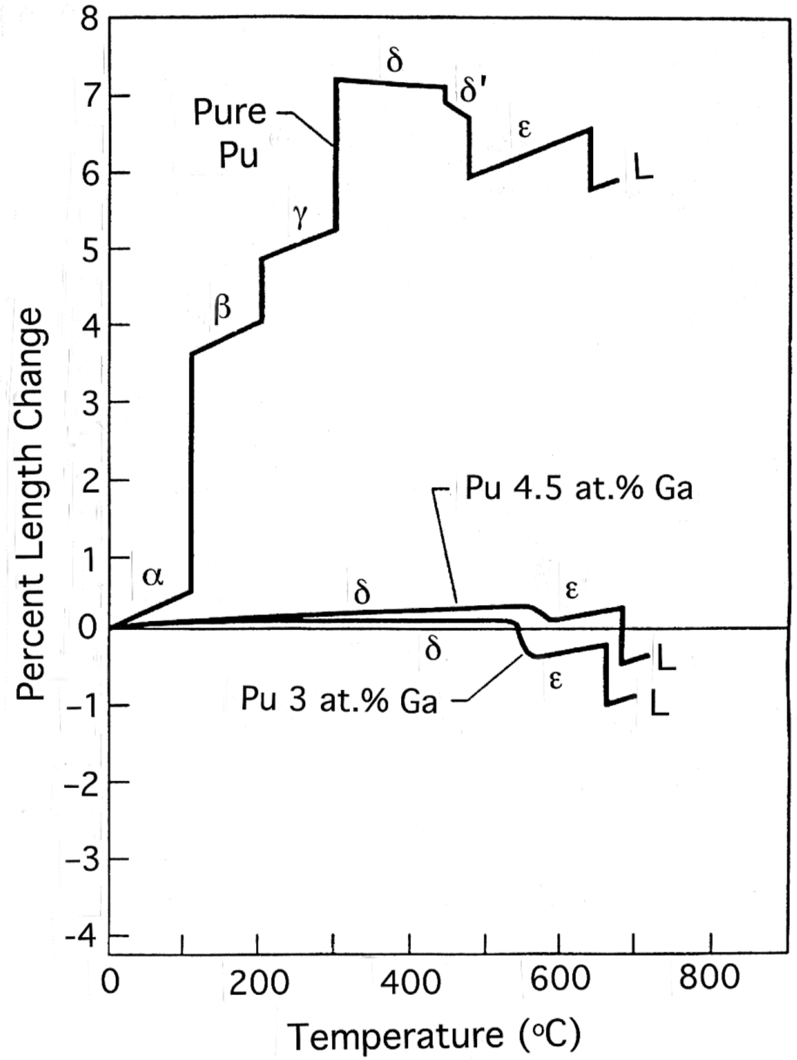



# The Homogenized Pu-Ga Alloy is a Single Phase FCC Alloy

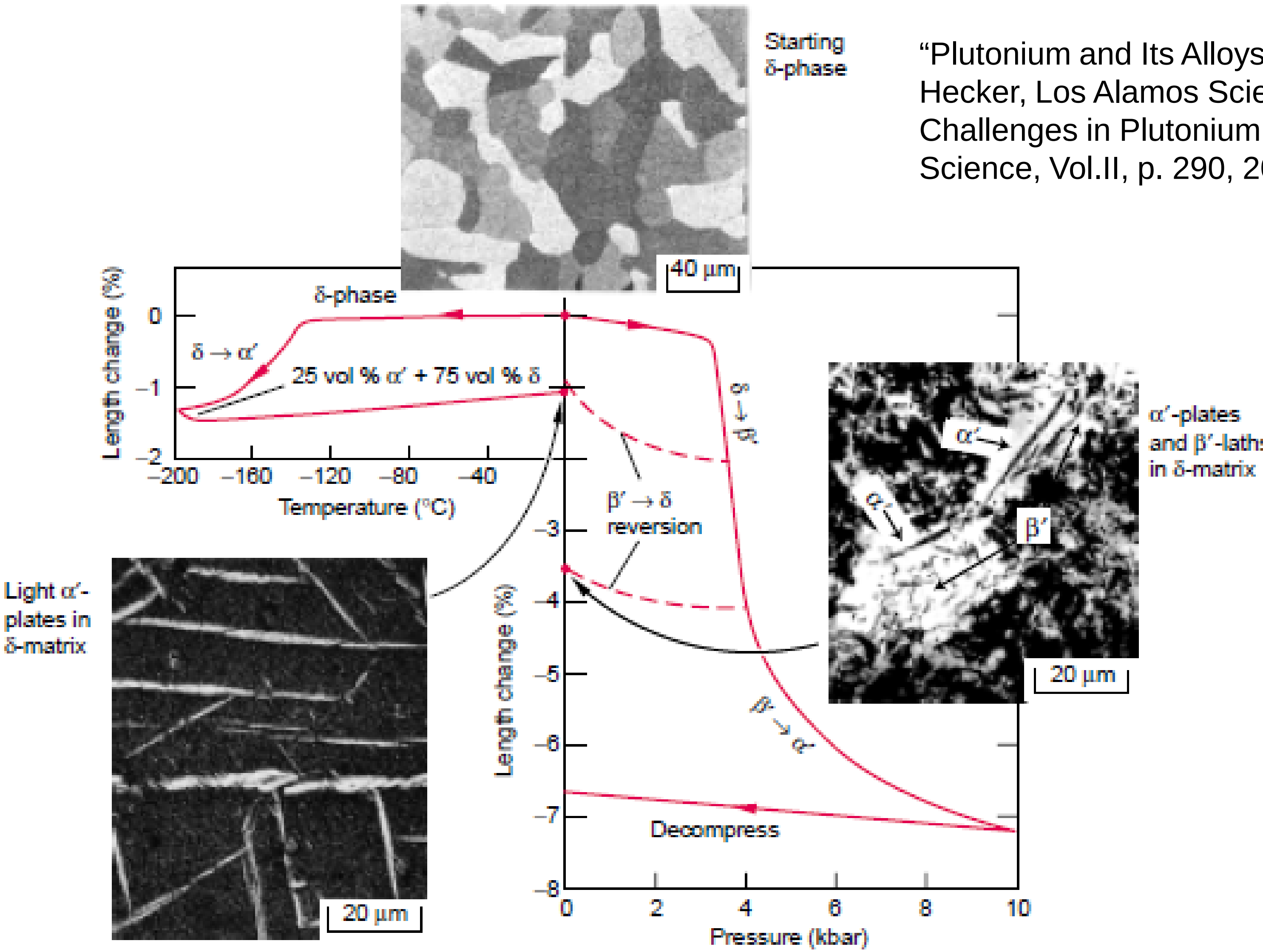



Original grains
Deformed elongated grains
Top roll
New grains forming
New grains growing
Bottom Roll
Recrystallization complete (new equiaxed grains)


Internal residual stress
Strength, hardness, ductility
Strength
Ductility
Hardness
Cold-worked and recovered
New grains
Grain size
Recovery
Recrystal-lization
Grain Growth



Percent Length Change
8
7
6
5
4
3
2
1
0
−1
−2
−3
-4
0
200
400
600
800
Temperature (oC)
Pure Pu
α
β
γ
δ
δ'
ε
L
Pu 4.5 at.% Ga
δ
ε
L
δ
ε
Pu 3 at.% Ga
L




"Plutonium and Its Alloys", S. Hecker, Los Alamos Science: Challenges in Plutonium Science, Vol.II, p. 290, 2000.

# Conclusions:

- Due to its nuclear properties, Pu will remain a material of global interest well into the future.
- Processing, Structure, Properties and Performance remains a good framework for discussion of Pu materials science
- Self-irradiation and aging effects continue to be central in discussions of Pu metallurgy
- Pu in its elemental form is extremely unstable, but alloying helps to stabilize Pu; but, questions remain  as to how and why this stabilization occurs.
- Which is true Pu-Ga binary phase diagram: US or Russian?
- Metallurgical issues such as solute coring, phase instability, crystallographic texture, etc. result in challenges to casting, processing , and properties modeling and experiments.
- For Ga alloyed FCC stabilized Pu, temperature and pressure remain as variables impacting phase stability.

Thank you for your interest!