Computational and physics-based modeling for the development of in-space welding technology

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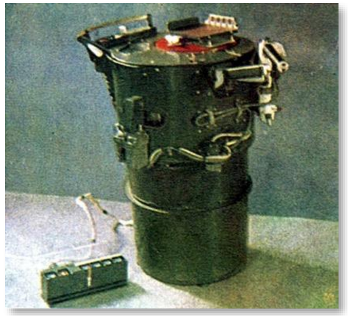
Loree Beth F Sowards

Timeline of In-Space Welding and Joining

ISAM
IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING



Progress in Space Stagnated and Moved to Parabolic Flights

It has been over 50 years since NASA has performed a weld in space.

1960s | 1970s | 1980s | 1990s | 2000s | 2010s | *2020s*

FIRST SPACE WELD
1969. Soyuz-6. Vulkan EBW, PAW, GMAW (USSR)

FIRST AMERICAN SPACE WELD
1973. Skylab. EBW, braze experiments (USA)

1979. Salyut-6. Isparitel braze coating (USSR)

1983. Salyut-7. Isparitel M, deposition (USSR)
1984. Salyut-7. UHT (USSR)
FIRST MANUAL OPEN SPACE WELD

1988. Mir, Yantar
EB melt/weld (USSR)

1993. Parabolic
CO_2 LBW (CAN)

1999. ISWE components went to MIR
USA/UKRAINE/RUSSIA **CANCELLED**

2021. SUBSA-BRAINS braze metal.
2023. Lockheed NASA Public-private JOINS.
2024. EBW in orbit by ThinkOrbital
2024. Parabolic fiber LBW Flight.
Ohio State and NASA

Parabolic Vulkan
experiment (USSR). 1965

Parabolic Skylab Materials
(USA). 1972

Parabolic Nd:YAG LBW (USA). 1988/89

Parabolic UHT Experiment. 1993
Parabolic ISWE Experiment. 1994

Drop Tower GTA Weld Experiment. 1998

Parabolic GHTA Weld Experiment. 2001

2018. New Ukrainian EBW Gun Patented

2024. Early Stage Innovations grant

2024-2026. Early Career Initiative:
LBW within TVAC

Background: Prior Work to Model In-Space Welding

- 1974. Brashears and Roberts. Force and thermal analyses were conducted of the M551 Metals Melting Experiment showing small effect of gravity on weld shape but influence on retention of porosity. https://ntrs.nasa.gov/citations/19740026763
- 1975. Muraki and Masubuchi. Finite element study of transient heat source in Skylab disc samples. https://ntrs.nasa.gov/citations/19750002894
- 1988. Zacharia et al. Welding Journal 1988: 53s-62s. Influence of surface tension, magnetohydrodynamics, and Marangoni in microgravity GTA weld pool.
- 1990s. Rubinsky et al. “Parametric studies of keyhole plasma arc welding examine the effect of plasma mass flow rate, plasma enthalpy, liquid metal surface tension, and jet shear on weldment shape under both normal and zero gravity.” “…keyhole and weld geometries are minimally affected by gravity, suggesting that data gathered under gravity can be used in planning in-space welding.” https://ntrs.nasa.gov/citations/19910054168
- 1995. Domey et al. Welding Journal 1995: 263s – 268s. Studied the effect of gravity on weld pool processes by numerical simulations. It was found that higher gravitational fields tend to enhance the convective flow within the weld pool affecting heat transfer, depth & width of the two-phase region, and pool depth-to width ratio.
- 2002. Nunes and Fragomeni. Acta Astronautica 50(1) 2002: 13-25. Modeled molten metal and electron beam impingement on ceramic fabric materials used for EVA. https://doi.org/10.1016/S0094-5765(01)00143-6
- 2021. Luchinsky et al. Multiphysics models of stationary arc torch and dynamical model of droplet detachment and transfer. Increased probability of porosity entrapment in meltpool, and unbounded wandering of spatter, and metal evaporation at hazardous levels in a habitat. https://ntrs.nasa.gov/citations/20210022016
- Relevant Work. Many research studies have modeled the solidification of alloys in microgravity with experiments aboard ISS supporting efforts including detailed models of aluminum brazing (Sekulic et al., 2022 SUBSA BRAINS Final Report). https://psi.ndc.nasa.gov/app/record/197716
- Structural Performance: In-space structures are a paradigm shift. Structures no longer need to survive launch loads.

Summary: Models have been sparsely applied to in-space welding and physical processes in space are demonstrably altered. Past work was largely in the infancy of FEA and CFD. The goal of this study is to bring a case study applying modern computational methods including CALPHAD and FEA to in-space welding.

Future: We have limited ability to mature welding technology for use towards In-space Assembly and Manufacturing (ISAM). Computational models will help us close gaps. Microstructure-properties-processing models are ripe for producing critical one-shot welds.

Space Environmental Effects that Influence Welding

Variable	Case 1: In Space	Case 2: Chamber Inside Habitat	Case 3: Inside Habitat	Case 4: Lunar Surface	Case 5: Martian Surface	Baseline: Earth	Capabilities Needed at Present
Gravity	μg	μg	μg	0.17 g	0.38 g	1 g	μg to 0.38 g
Atmosphere	Vacuum (10^{-19} Pa)	Vacuum (10^{-4} Pa)	At least 21% O_2 and no more than 101 kPa	Vacuum (10^{-9} Pa) or Habitat (varies)	$95CO_2$-$2.6N_2$-1.9Ar-$0.2O_2$-0.06CO (0.6 kPa) or Habitat (varies)	$78N_2$-$21O_2$-0.9Ar-0.1other	HV (10^{-1} Pa) UHV (10^{-5} Pa) XUHV (10^{-9} Pa)
Temperature	Extreme Low (e.g., ISS Exterior: 120 K – 395 K)	~ 293 K	~ 293 K	40 K – 400 K	133 K – 300 K	~ 293 K	40 K – 400 K
Space Suit Required	Yes	No	No	Yes	Yes	No	

*Table in blue was adapted from original source (K. Masubuchi, J.Weld.Soc, 59(6) p.421-427 (1990)) and expanded upon.

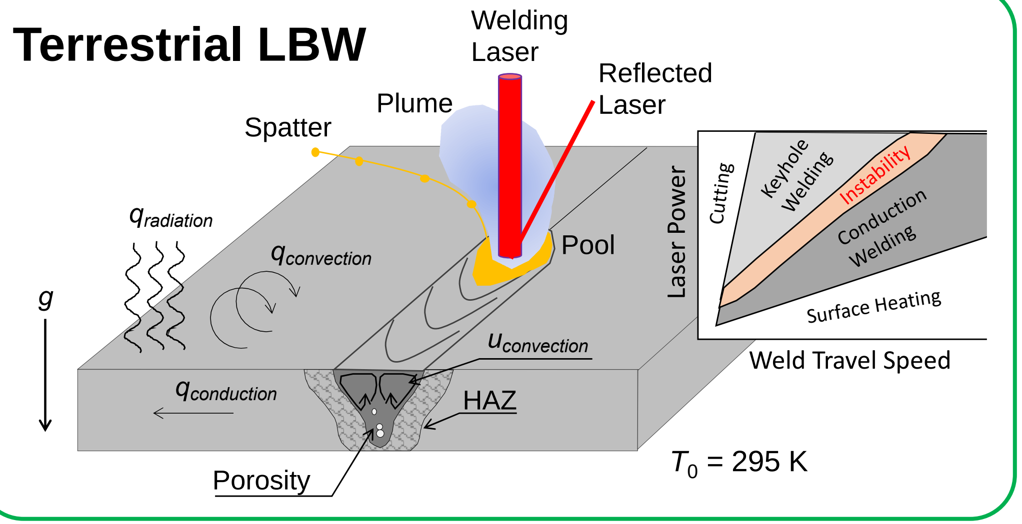
Reduced gravity is unique among the above effects in that it cannot be reproduced for prolonged periods on earth.

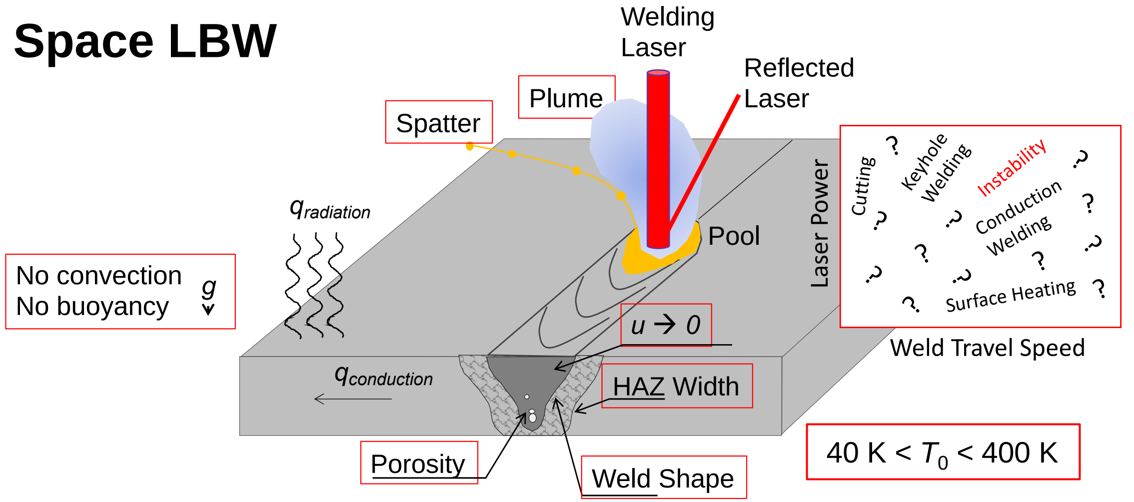
Current Work: Integrate existing capabilities within NASA to investigate space environmental effects on welding processes to inform computational models, pursue public-private partnerships to develop and implement relevant in-space welding and modeling technologies, disseminate data and encourage open-source models moving forward.

Need: Computational Models for In-Space Welding

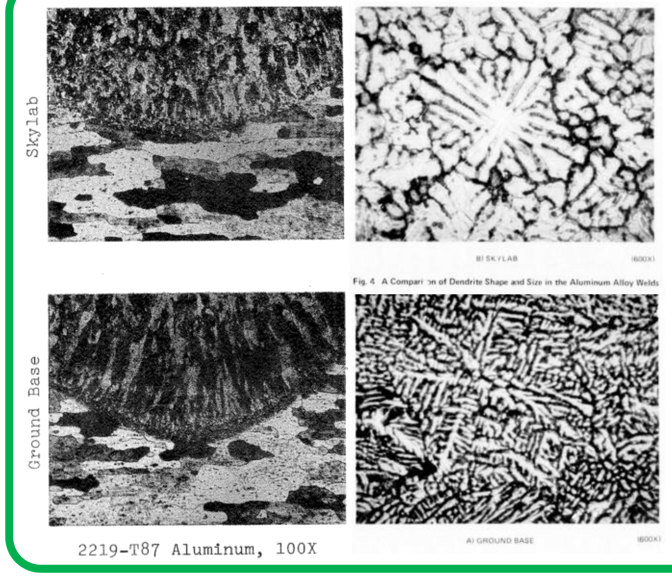
- **Problem:** Welding in space is subject to 1) large temperature variation, 2) reduced gravity, and 3) vacuum/reduced atmosphere compared to terrestrial welds. Weld development is Edisonian and there are no welding process parameter windows for critical one-shot welds in space that account for these physical changes.
- **Opportunity:** Use computational materials modeling as an enabling tool to inform experimental design for rapid weld parameterization by interrogating process physics in a virtual environment. Inform and validate models with parallel experimental approaches.
- **Metrology Needs:** Test platforms that provide the correct physics of space, characterization of the welds, thermophysical properties particularly above the liquidus temperature, heat-source coupling/reflection, spatter formation (MMOD), structure-property-process data, etc.
- **Issue #1** Weld heat transport has profound effect on size of a weld and its metallurgical transformations and hence weld properties:
  - Temperature gradient and cooling rate are proportional to thermal conductivity and T_0^2
- **Issue #2** Reduced gravity reduces buoyancy-induced convection:
  - Development of weld pool shape and porosity evolution are altered, and chemical effects become dominant, e.g., surface-active elements influence weld penetration due to thermocapillary flow. (minute alloy chemistry changes are important)
- **Issue #3** Reduced pressure/vacuum in space:
  - Heat transport is dominated by radiation and conduction rather than by convection. Weld shape and width, and weld strength will be influenced by change in weld cooling.
  - Reduced pressure influences laser beam keyhole stability, evaporation of volatile species, safety issues, etc.
- Physics of Terrestrial vs Space LBW are compared to the right.

Modeling/Measurement opportunities indicated in red.





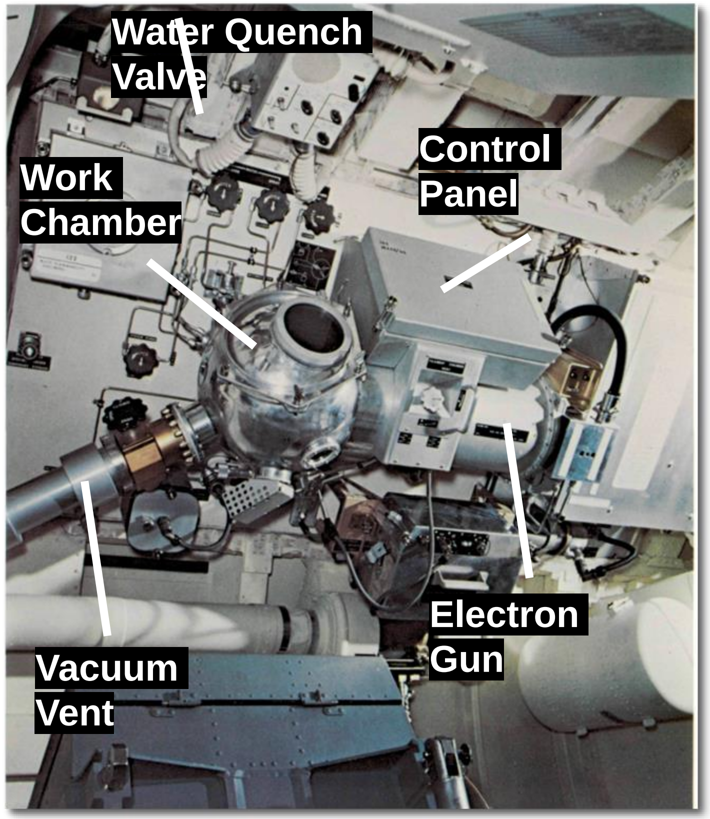
Skylab Electron Beam Welds. Structure-Property-Processing

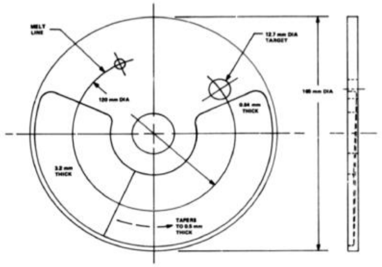


- In the ground base samples, the dendrites are much larger at the root region than at the crown region. In the Skylab samples, the difference in size is much smaller.
- Concluded some unknown combination of ***G*** and ***R*** were different between ground and flight welds. G. Busch. Grumman Report (1976). https://ntrs.nasa.gov/citations/19770024270

Structure

Processing



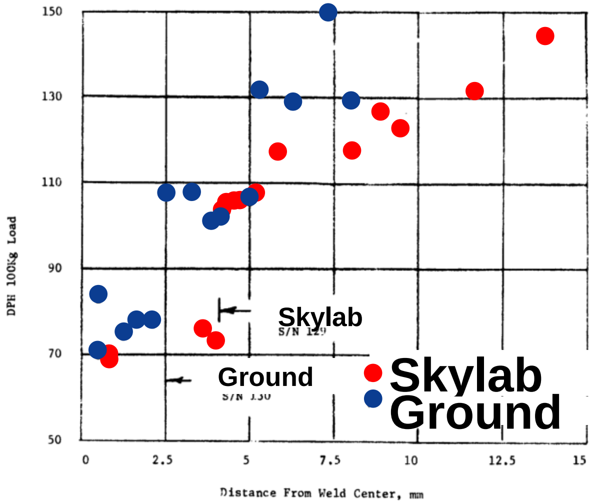


Travel speed = 1.61 cm/s, E = 20 kV, I = 50-80 mA

Alloys: Stainless Steel (304), Aluminum (2219-T87), CP Tantalum.

After 2 hr space vent, Vacuum = 10^{-4} Torr ($1.3 \cdot 10^{-2}$ Pa)

Properties



R.E. Monroe. NASA CR-129041 (1974). https://ntrs.nasa.gov/citations/19750002046

- Monroe (1974) produced hardness plots for full penetration Skylab and Ground welds.
- Li et al. (1976) concluded that no significant differences in hardness were observed between the ground base and Skylab samples of 2219. Tantalum discs did show a significant difference, but no explanation was provided.

Process Model: Evolution of FEA and Mesh Refinement

1974 Lockheed Martin Analysis. >370 Nodes

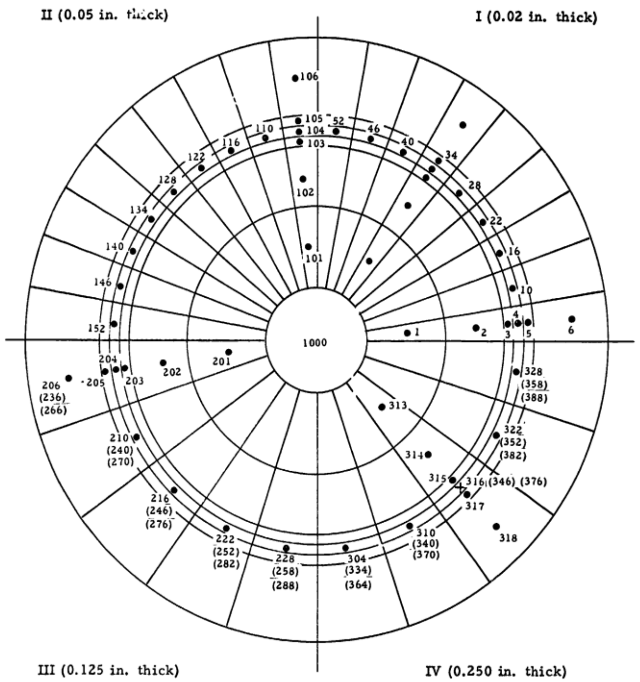
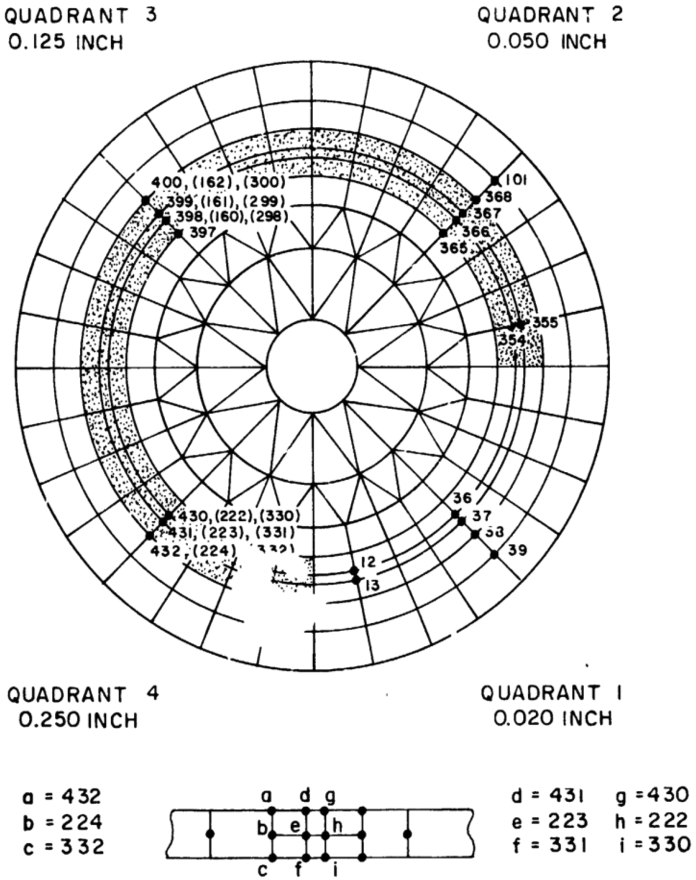


FIGURE 4. NODAL POINT ARRANGEMENT FOR THERMAL CALCULATIONS

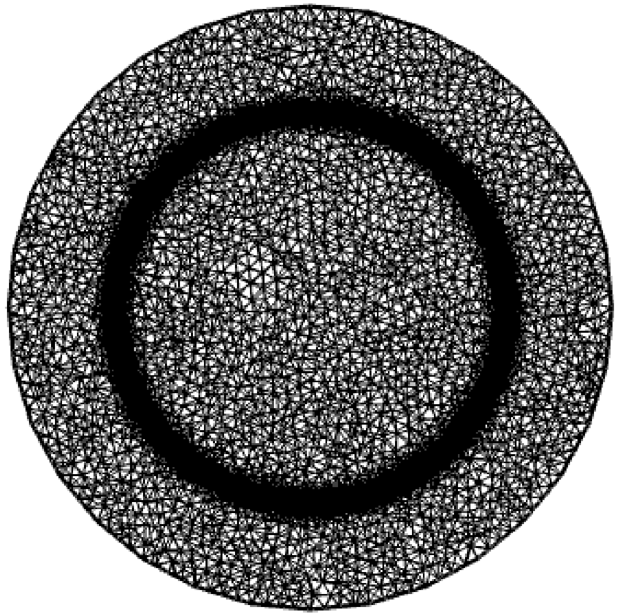
1974. Brashears and Roberts. Little detail provided.

1975 MIT Analysis. 232 Elements & 216 Nodes.



1975. Muraki and Masubuchi. Conduction and Radiation with constant thermophysical properties. Ability to consider melting and solidification.

Current Analysis. 166K+ Elements.

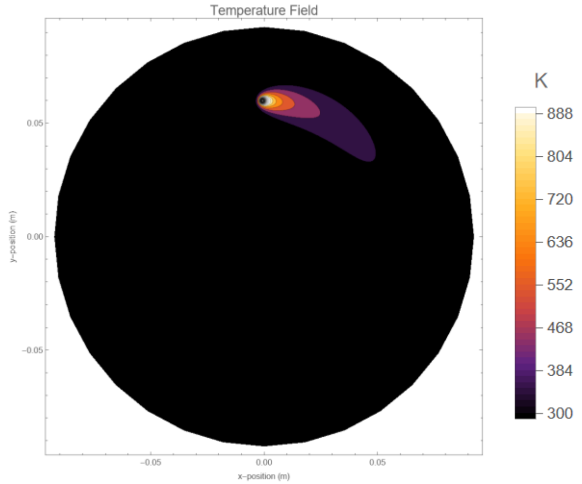
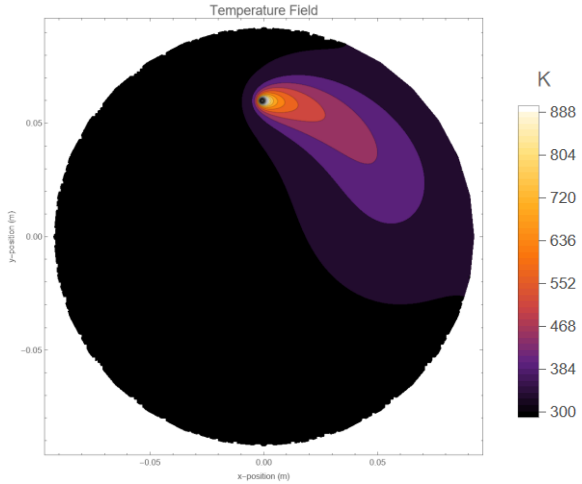
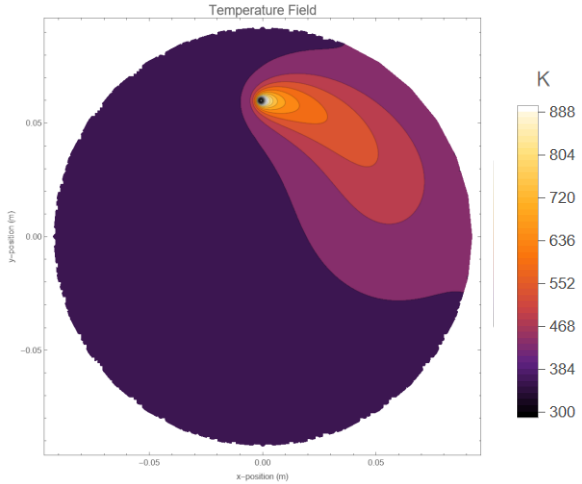
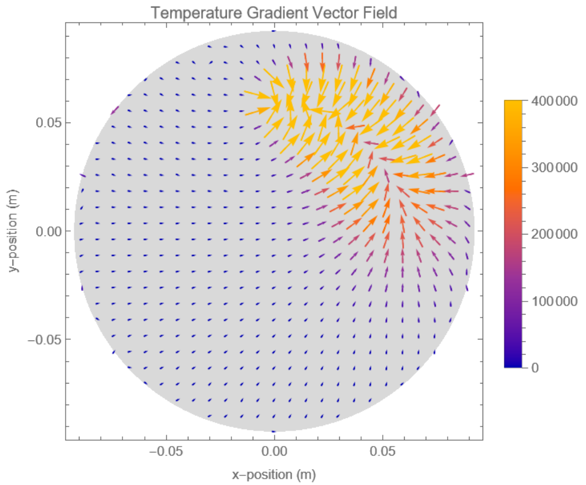
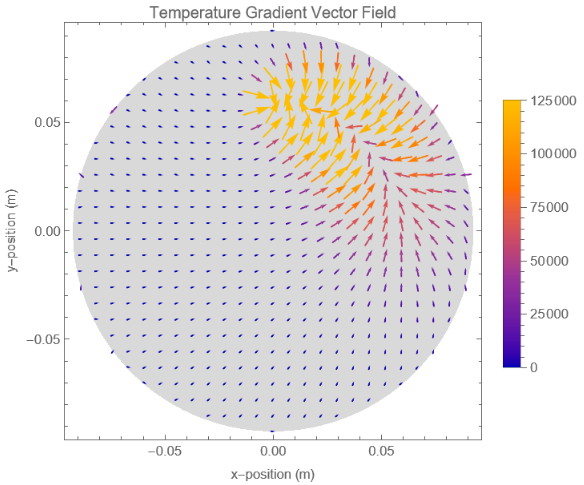
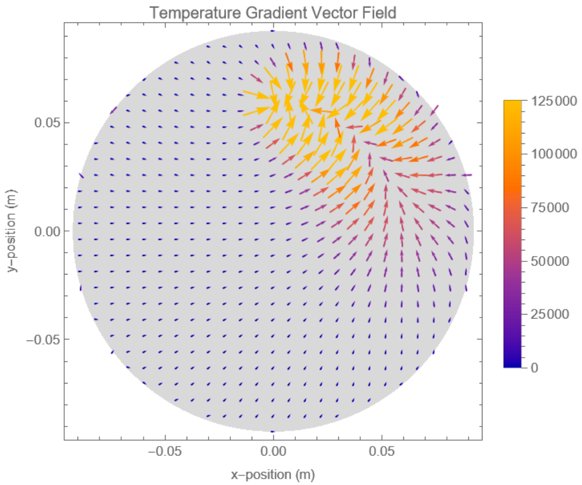


Mathematica v.14
- Temperature-dependent thermophysical properties
- Distributed heat source (assumed distribution for EBW)
- Radiation, internal heat conduction, vaporization BCs
- Phase change melting/solidification are being tested

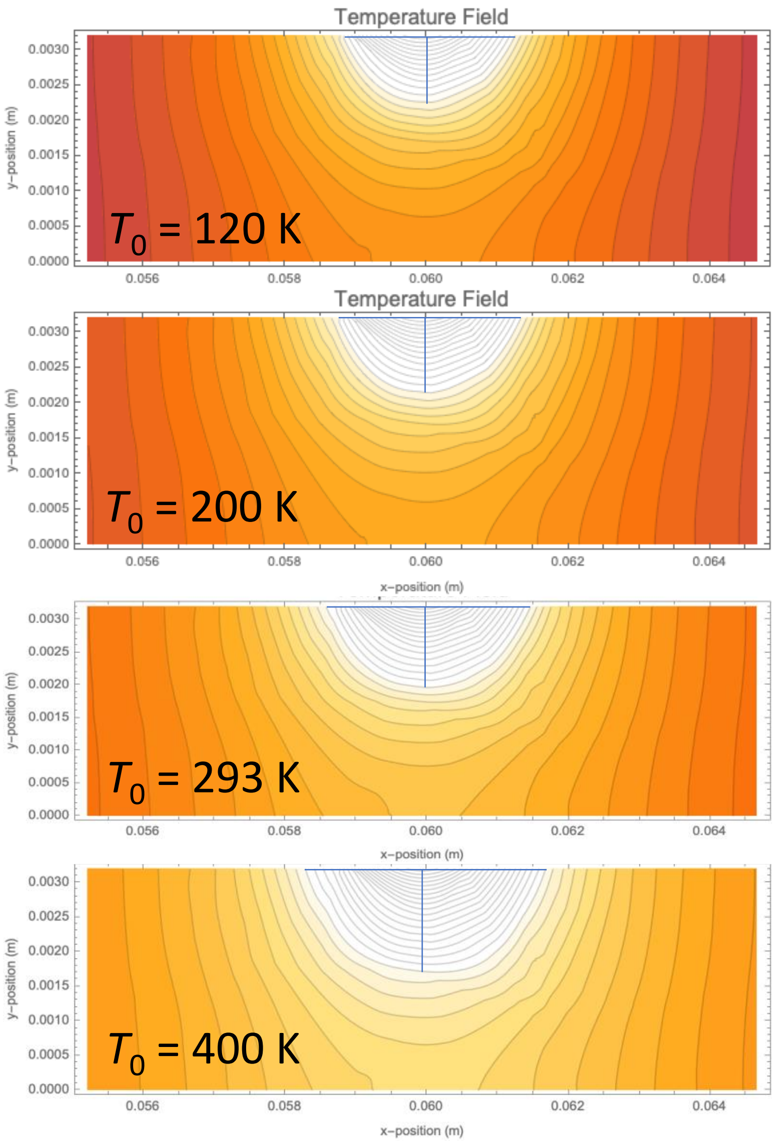
Navier Stokes solution and complex boundary conditions in further iterations

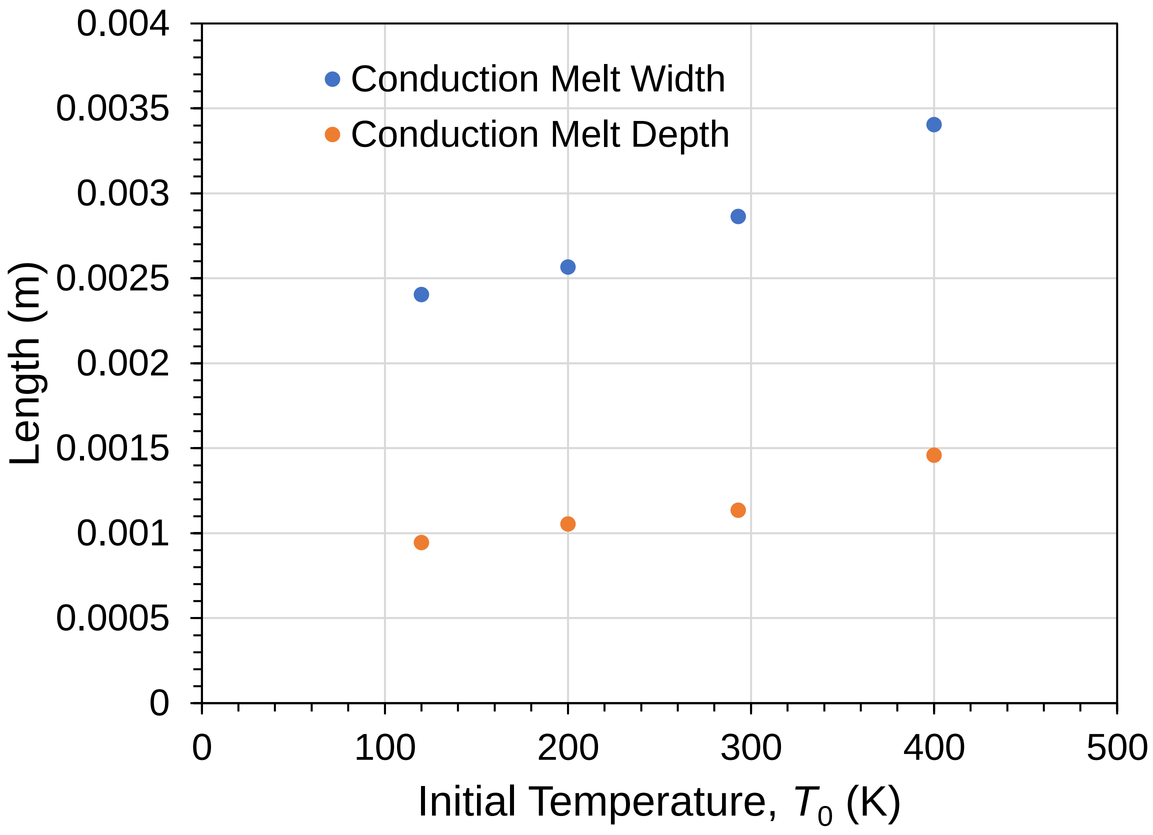
T and G*R Maps of Disc at 100 K, 293 K, & 400 K

IN-SPACE SERVICING, ASSEMBLY, AND MANUFACTURING

T_0 = 100 K	T_0 = 293 K	T_0 = 400 K
		
		

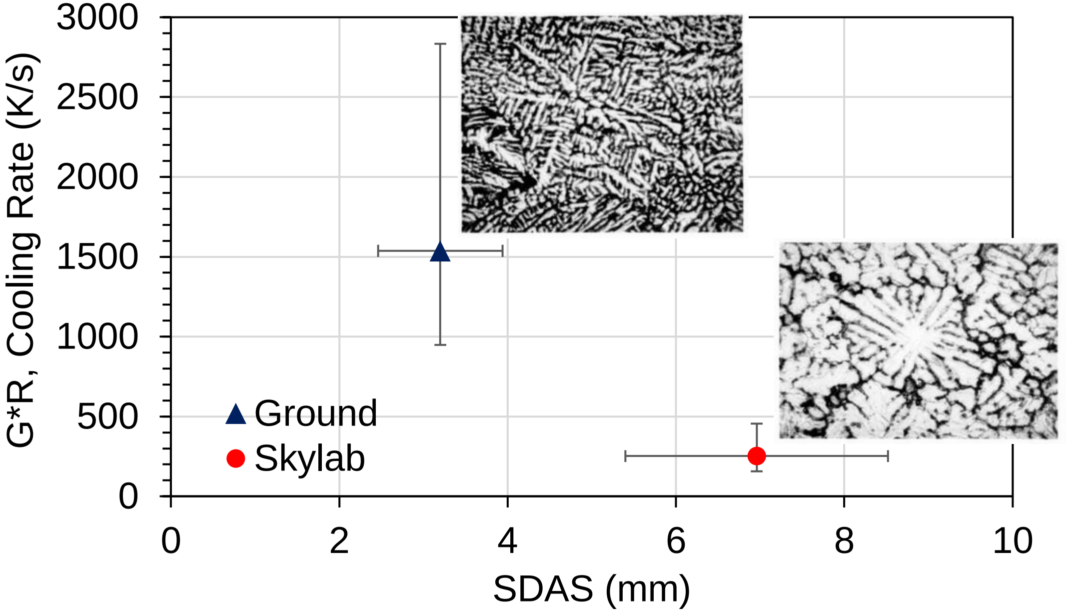
Effect of T_0 on Conduction Melt Dimensions





- Melt zone decreases in volume as T_0 decreases
- Constant D/W ratio of ~0.4
- Analytical (Rosenthal 3D) model predicts increasing melt size at low T when using low-T thermal diffusivity

Comparison of Model and Empirical G*R



$$\lambda_2 = (143.73x^{-0.356})(G^*R)^{-0.43}$$

Brice and Dennis. *Met Trans A* 46 2015: 2304-2308.
DOI: 10.1007/s11661-015-2775-x (Wire-fed electron beam additive manufacturing process on Al-Cu)

λ_2, Secondary dendrite arm spacing (μm)
x, Cu content of AA2219 Skylab discs (6.2 wt.%)
G, Thermal gradient (K/m)
R, Growth rate (m/s) (Ground ~Travel speed = 0.015 m/s)
G*R, Cooling rate through solidification interval (K/s)

Condition	SDAS (um)	Empirical GR (K/s) from equation above	Empirical G (K/m) from equation above	R (m/s)	Macro Gradient (K/m)
Ground	3.2 +/- 0.74 (*N* = 26)	1537	$104*10^3$ K/m	0.015	$125*10^3$
Skylab	6.96 +/- 1.56 (*N* = 22)	252	$17*10^3$ K/m	Unknown due to microgravity solidification	Fluid transport neglected in model

The lack of convective currents in microgravity means heat and solute are removed from the solidification front primarily by diffusion, resulting in slower growth rates and larger dendrite arms.

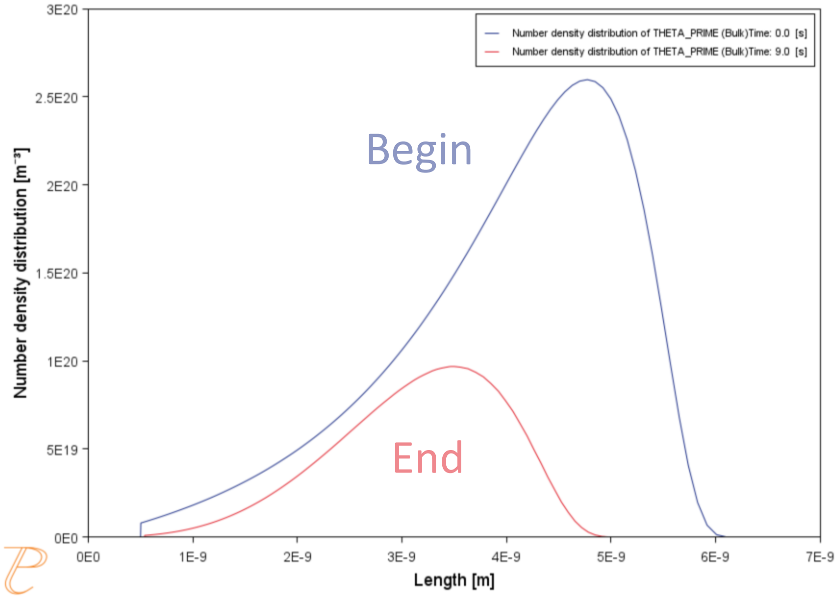
Glicksman, et al. (1986). Physics Today, 39(8), 60-67. Glicksman, et al. (1992). Met Trans A, 23(4), 1531–1542.

Properties: Predictions of Precipitation Hardening

- Precipitate dynamics via Kampmann-Wagner numerical (KWN)
  - Follow nucleation, growth, coarsening (and solvation) of precipitates
- Implemented by Thermo-Calc's TC-Prisma module (2024b version)
  - Using aluminum-base databases TCAL9 & MOBAL8
- Apply thermal history from FEA simulation to predict new precipitate distribution and resulting hardness at various locations away from fusion zone

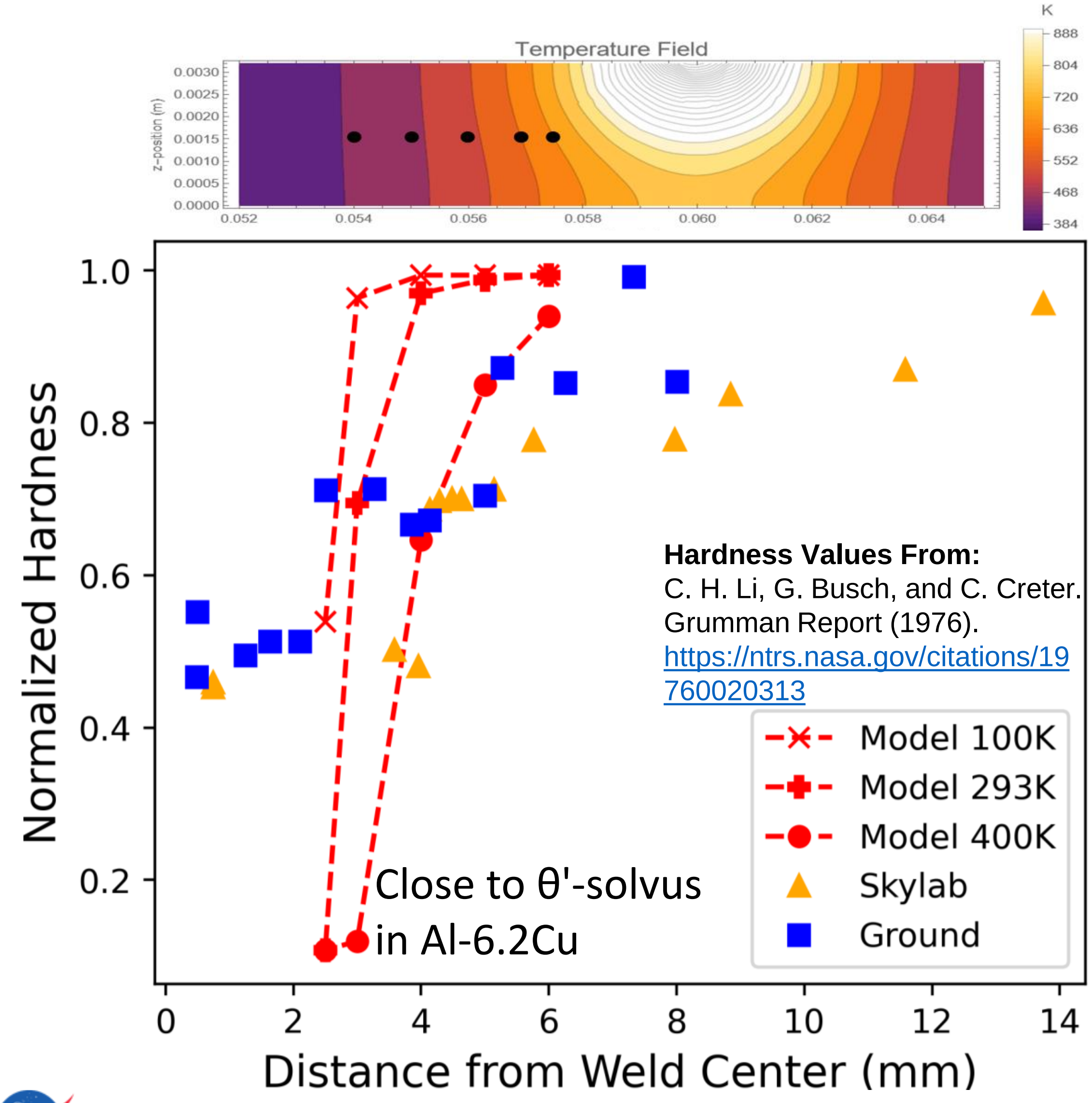
Why not report hardness in fusion zone?
- Microstructure (grains, eutectic, etc.) remodeled due to melting, mixing, and re-solidification
- Precipitate evolution within non-melted regions could be captured if thermal history known (thermo-fluid dynamical model needed?)
- Chemistry altered due to vaporization in melt pool

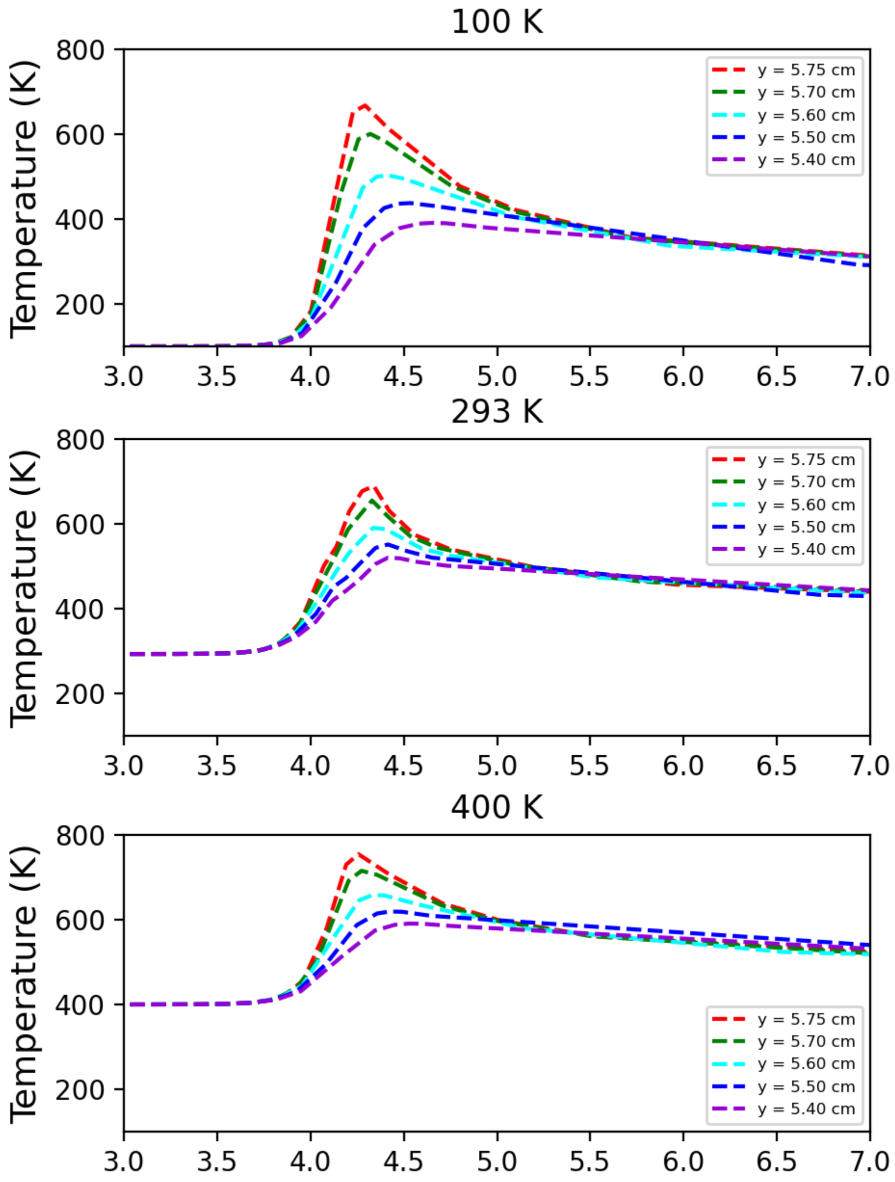
- Assumptions/Limitations:
  - Assumed initial plate-like θ' (Al_2Cu) precipitate size distribution from literature (room temperature aged for two years after T87 treatment: work-hardened & artificially aged)
  - Limited dynamics of new nucleation sites (TC-Prisma cannot nucleate plate-like precipitates on dislocations as would be expected for theta-prime)
  - Constant aspect ratio of precipitates (AR = 10)
  - Only considering θ' (major contribution to hardness)
  - Substituting Al-Cu-Fe-Mn quaternary for 2219
  - Included solid solution and grain boundary strengthening (*de minimis* contribution), but not grain growth (would only further minimize)
  - Used Deschamps model for Al precipitation strengthening



Manikandan *et al.*, *Materials Characterization*, 2022, doi: 10.1016/j.matchar.2022.111973.
Deschamps and Brechet, *Acta Materialia*, 1998, doi: 10.1016/S1359-6454(98)00296-1.

Properties: Hardness by Starting Disc Temperature





Summary and Conclusions

- Goals set forth are to increase awareness in the resurgence of in-space welding and increase interest to fill gaps pertaining to modeling.
- Opportunities in Modeling: Bottom Line: We have limited ability to mature welding technology for use towards In-space Assembly and Manufacturing (ISAM). Computational models will help us close gaps. Structural performance. In-space structures are a paradigm shift. Structures no longer need to survive launch loads.
- Example FEA thermal model capable of reproducing Skylab-like conditions at 100 K, 293 K, and 400 K; some complications in thermophysical properties at 40 K, leading to computational difficulties.
- Thermal history from FEA can be linked to precipitation models (CALPHAD and KWN via Thermo-Calc and TC-Prisma, respectively). These precipitation models demonstrate expected θ' solvation and softening at high temperatures in heat affected zone at all initial temperatures.
- Additional, validated models will be needed to assess evolution of fusion zone. *i.e.* a coupled solidification – dynamical thermofluids models (*e.g.* phase field – lattice Boltzmann).
- There is need for high-fidelity validation datasets collected from relevant benchmark experiments in reduced pressures, reduced gravity, and varied temperatures.