SAND2011-4430C

Bulk Enthalpy Calculations in the Arc Jet Facility at NASA ARC

June 28, 2011

Corinna S. Thompson
Mechanical Engineer

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- Background on Arc Jets
- Introduction to Enthalpy in Ames Arc Jets
- Method used to improve on Enthalpy Calculations
- Results
- Summary and Concluding Statements

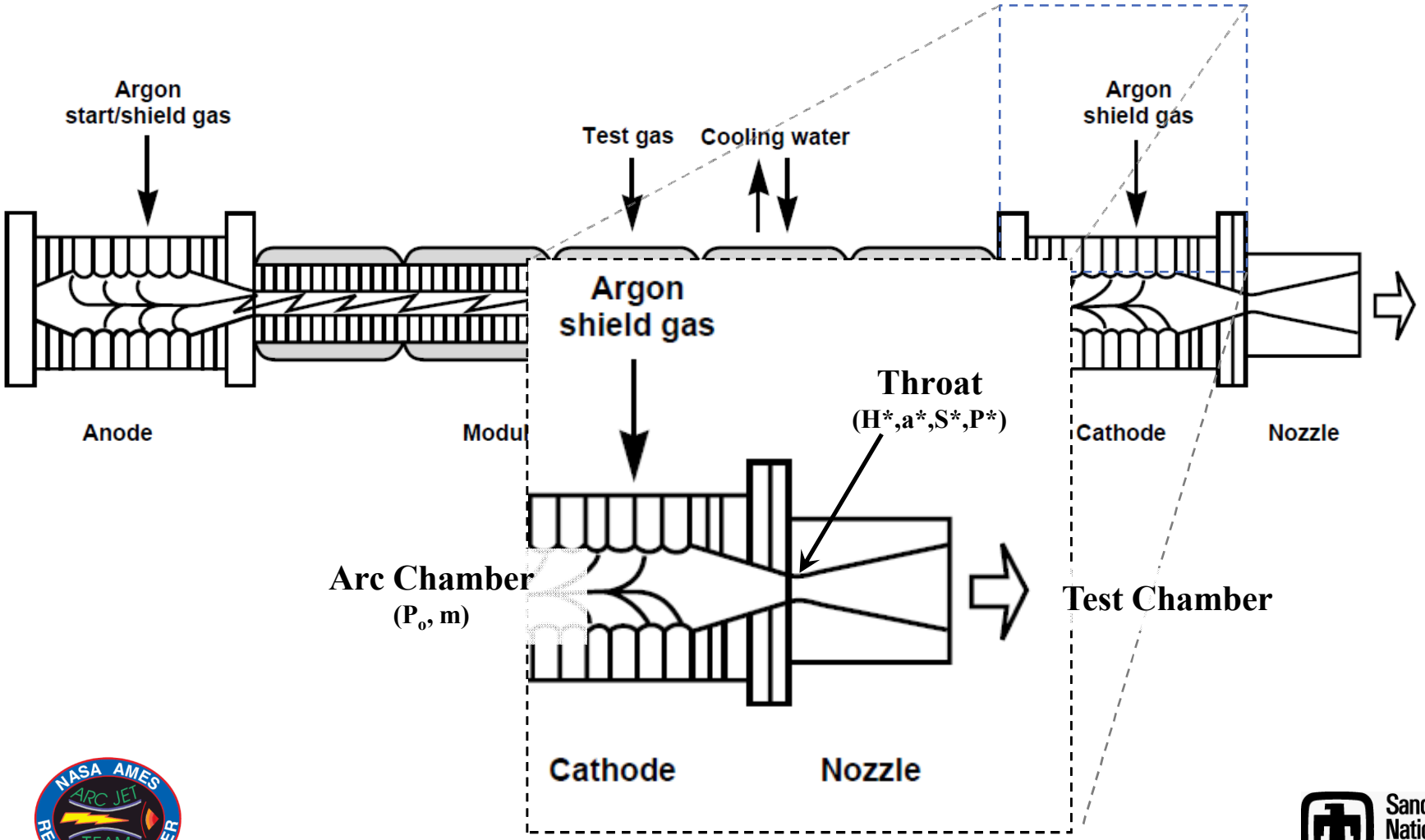
Background

- Why enthalpy is important – materials response modeling
- For an inviscid adiabatic flow total enthalpy is conserved
- Inference of total enthalpy from calorimetric measurements (Fay-Riddell) [Profiles]

$$H_{\mathrm{CL}} = \frac{\sqrt{R_{\mathrm{eff}}}}{K} \frac{q_{\mathrm{stag}}}{\sqrt{p_{stag}}}$$

- Inference of total enthalpy from energy loss in the system

Arc Jet Operation



Bulk Enthalpy Correlations

- **1964 Winovich**

For enthalpies 2.3-23 MJ/kg

$$H_0 = (123/\sigma)^{2.52}$$

- **1993 Shepard, Milos, Taunk**

$$H_0 = (158.7/\sigma)^{1.971}$$

Sonic Flow Parameter (units of *s/m*):

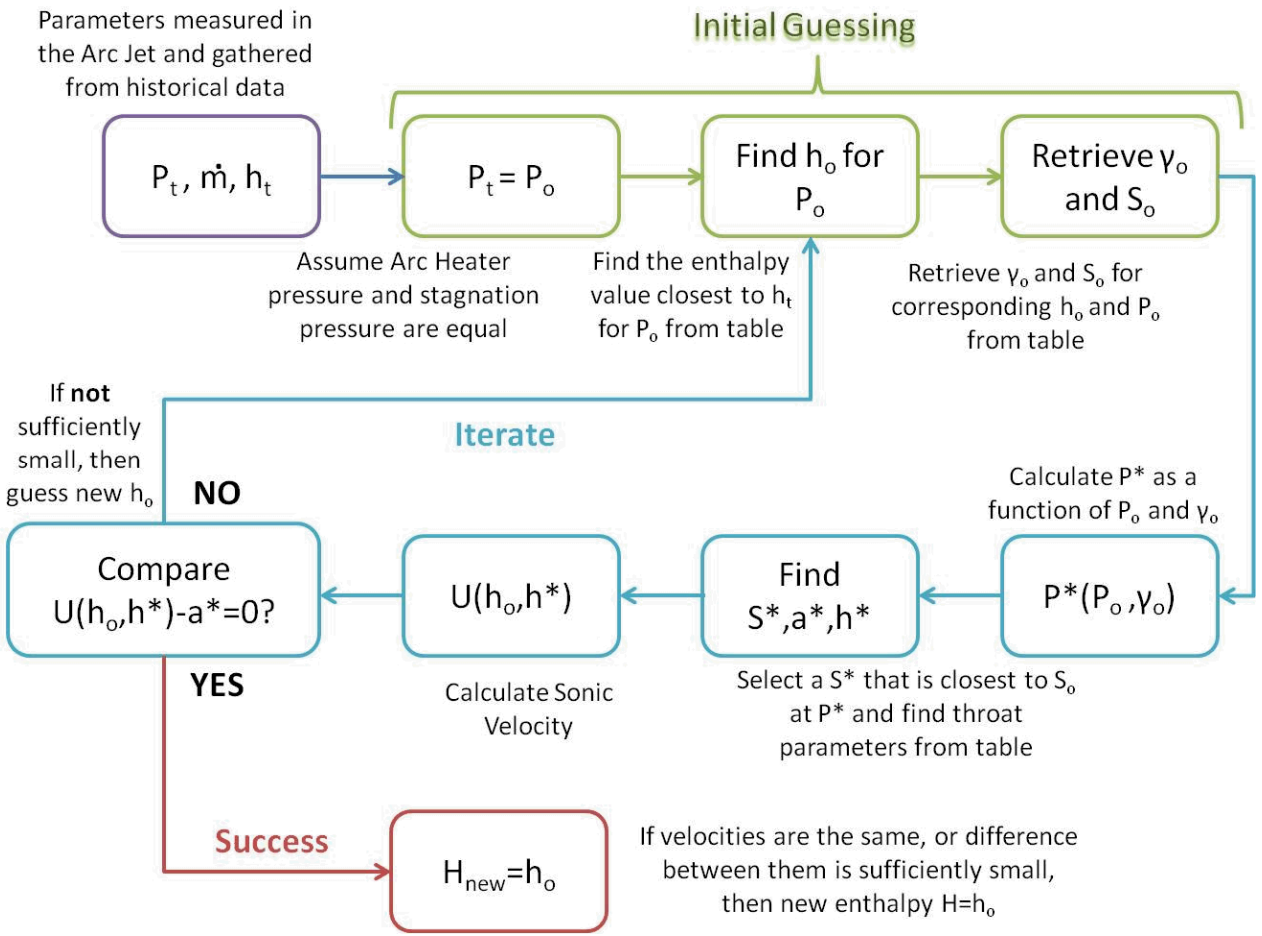
$$\sigma = w/A^* P_0$$

Goals/Motivations

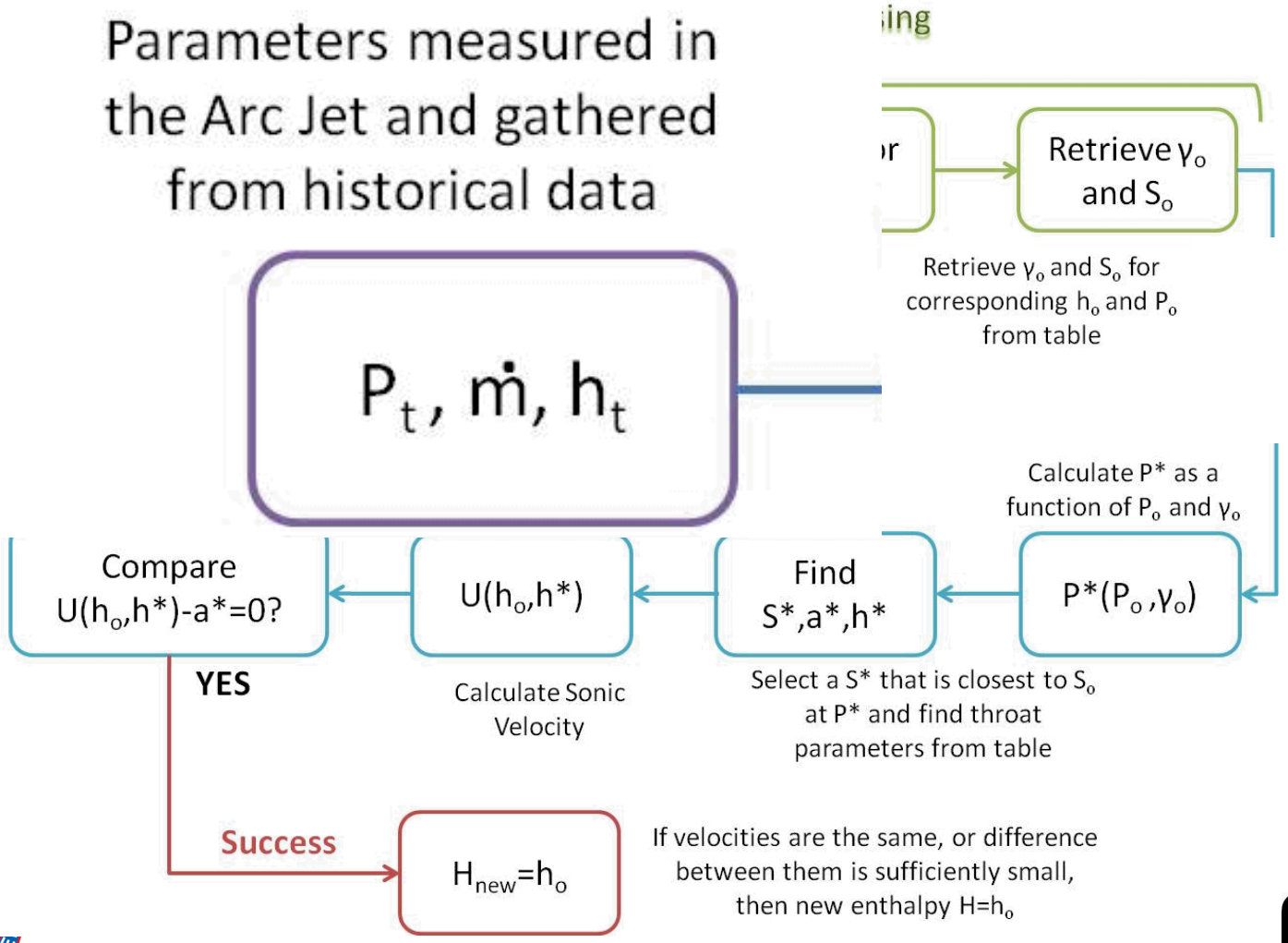
$$H_0 = (C/\sigma)^x \longrightarrow H_0 = (C/\sigma)^2$$

- Does *C* depend on argon content?
- How does a dimensionally correct calculation compare with the current calculations?
- How does a dimensionally correct calculation compare with a different enthalpy calculation?

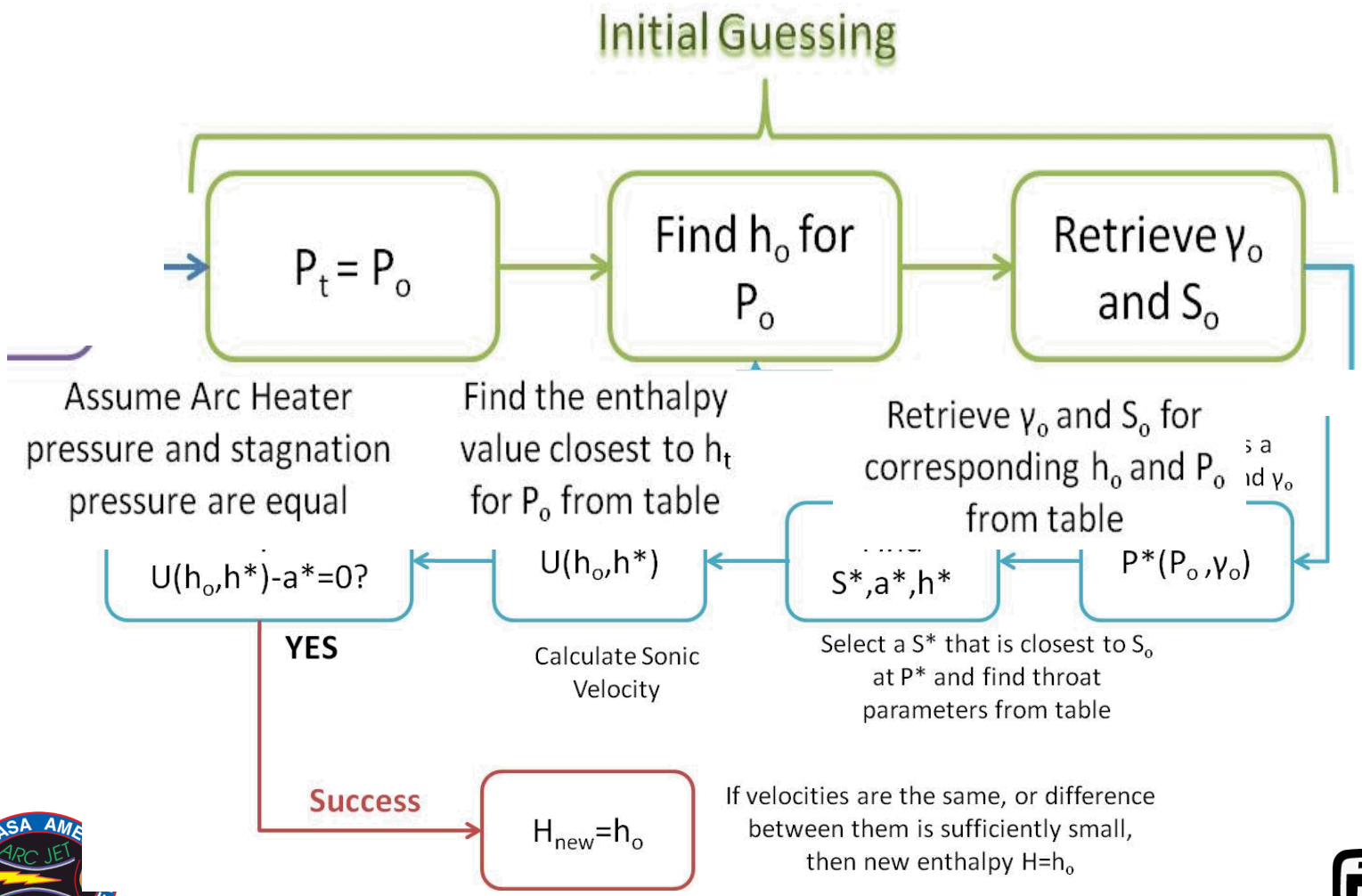
Method


Parameters measured in the Arc Jet and gathered from historical data
Initial Guessing
P_t, $\dot{m}$, h_t
$P_t = P_o$
Find h_o for P_o
Retrieve γ_o and S_o
Assume Arc Heater pressure and stagnation pressure are equal
Find the enthalpy value closest to h_t for P_o from table
Retrieve γ_o and S_o for corresponding h_o and P_o from table
If **not** sufficiently small, then guess new h_o
Iterate
NO
Calculate P* as a function of P_o and γ_o
Compare $U(h_o,h^*)-a^*=0$?
$U(h_o,h^*)$
Find S^*,a^*,h^*
$P^*(P_o,\gamma_o)$
YES
Calculate Sonic Velocity
Select a S* that is closest to S_o at P* and find throat parameters from table
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$

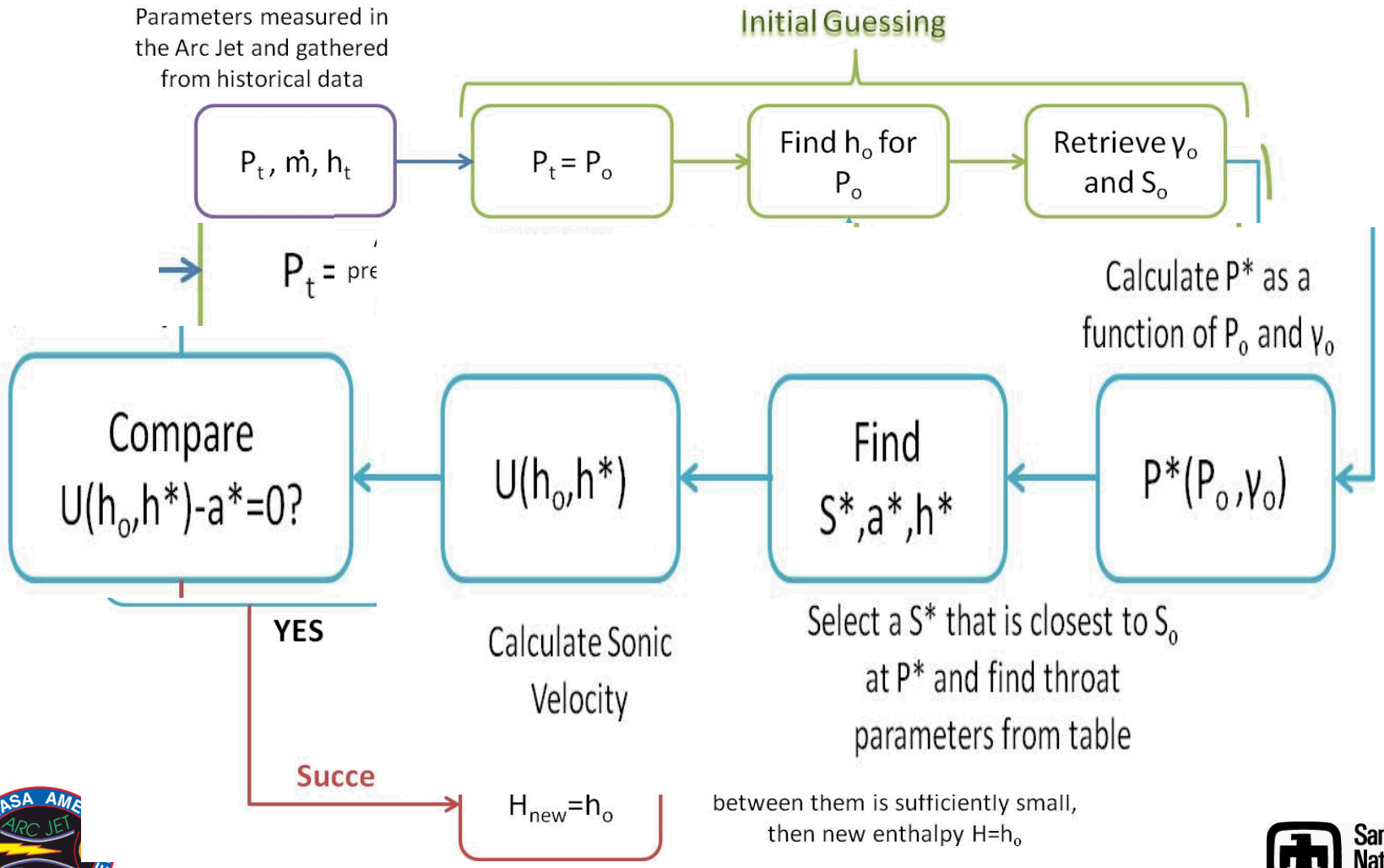
Method


Parameters measured in the Arc Jet and gathered from historical data
$P_t, \dot{m}, h_t$
Retrieve γ_o and S_o
Retrieve γ_o and S_o for corresponding h_o and P_o from table
Calculate P* as a function of P_o and γ_o
$P^*(P_o, \gamma_o)$
Find S*,a*,h*
Select a S* that is closest to S_o at P* and find throat parameters from table
$U(h_o,h^*)$
Calculate Sonic Velocity
Compare $U(h_o,h^*)-a^*=0$?
YES
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$

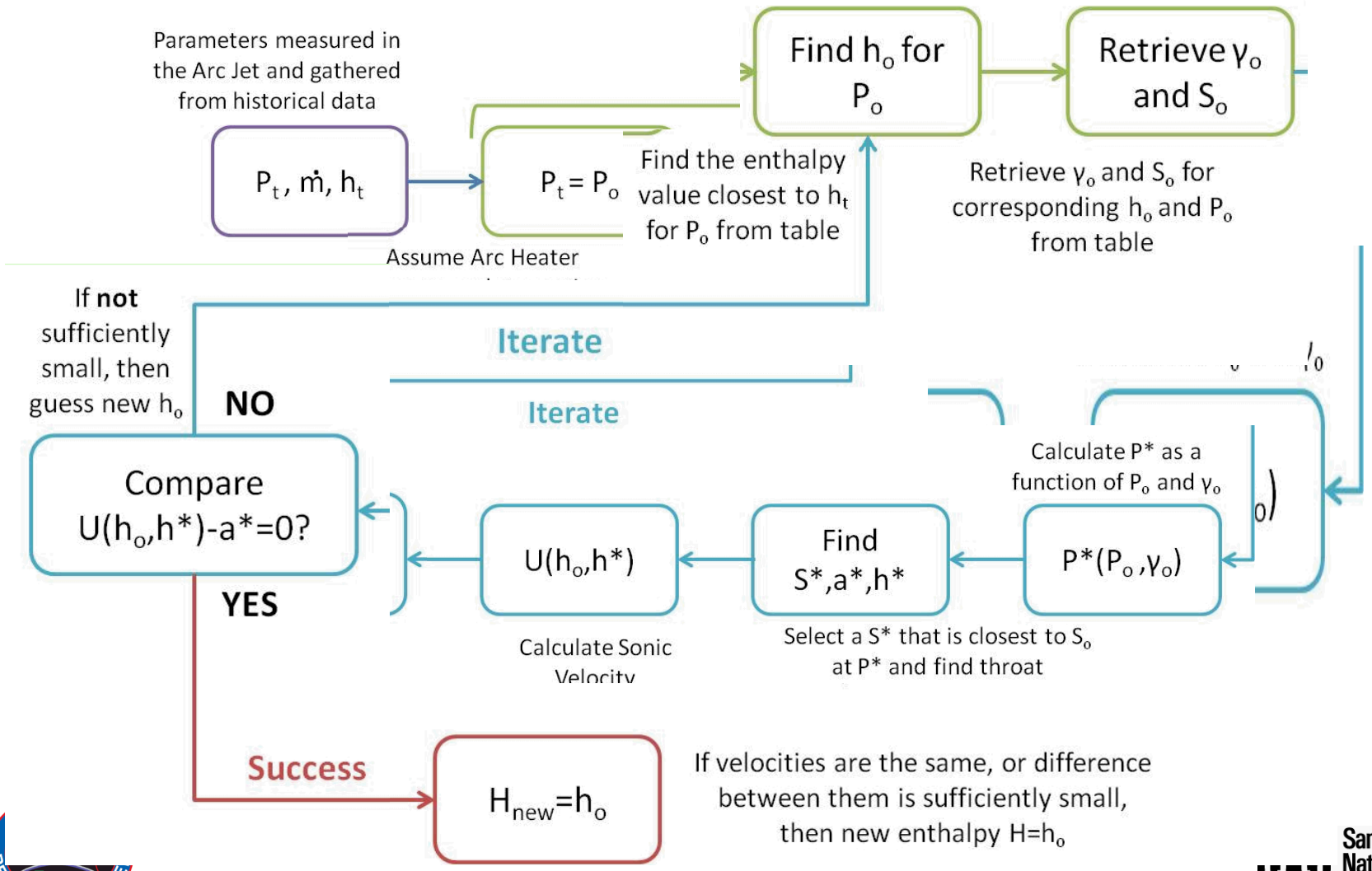
Method


Initial Guessing
$P_t = P_o$
Find h_o for P_o
Retrieve γ_o and S_o
Assume Arc Heater pressure and stagnation pressure are equal
Find the enthalpy value closest to h_t for P_o from table
Retrieve γ_o and S_o for corresponding h_o and P_o from table
$U(h_o,h^*)-a^*=0$?
$U(h_o,h^*)$
S^*,a^*,h^*
$P^*(P_o,\gamma_o)$
YES
Calculate Sonic Velocity
Select a S* that is closest to S_o at P* and find throat parameters from table
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$

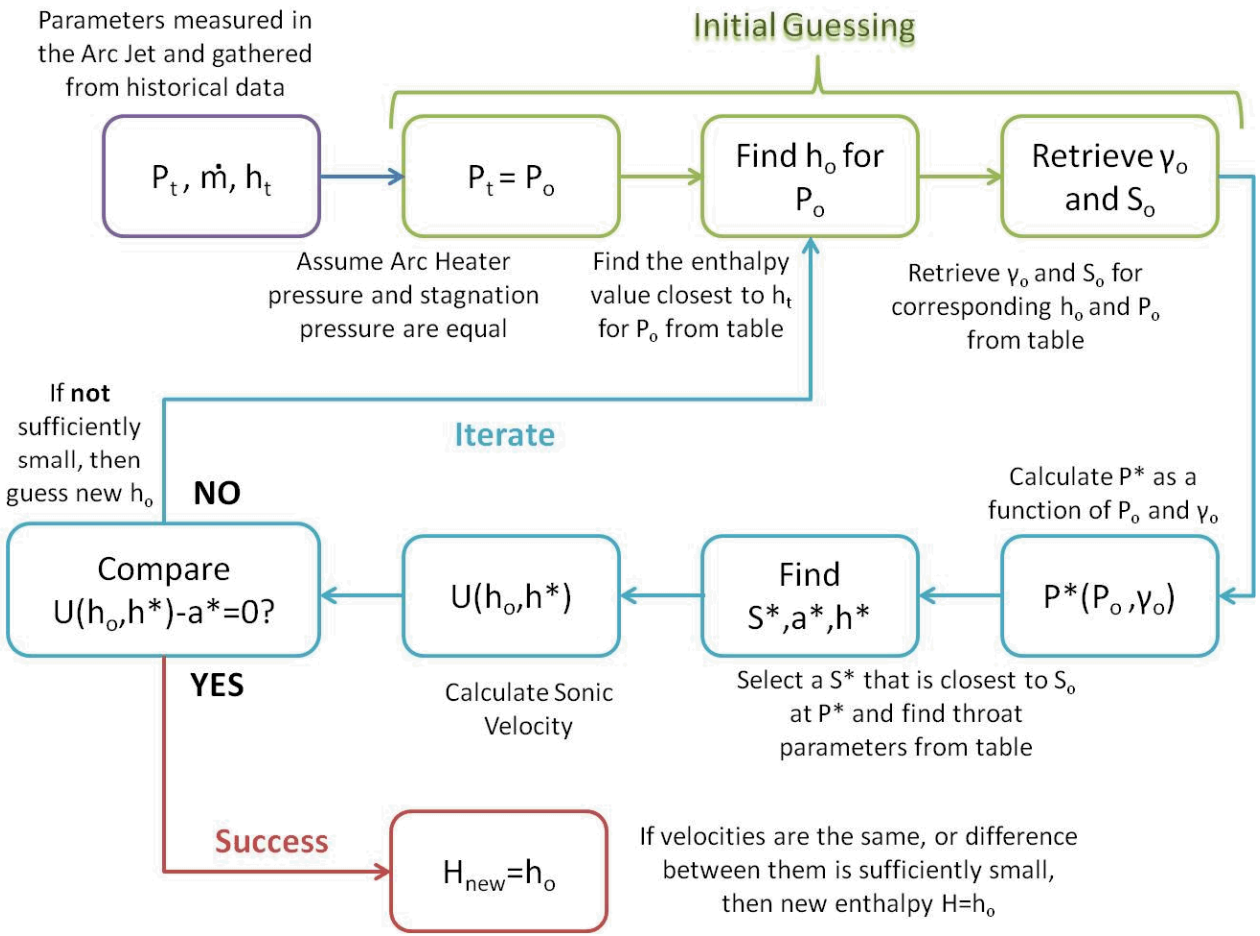
Method


Parameters measured in the Arc Jet and gathered from historical data
Initial Guessing
P_t, $\dot{m}$, h_t
$P_t = P_o$
Find h_o for P_o
Retrieve γ_o and S_o
P_t = pre
Calculate P* as a function of P_o and γ_o
Compare $U(h_o,h^*)-a^*=0$?
$U(h_o,h^*)$
Find S^*,a^*,h^*
$P^*(P_o,\gamma_o)$
YES
Calculate Sonic Velocity
Select a S* that is closest to S_o at P* and find throat parameters from table
Succe
$H_{new}=h_o$
between them is sufficiently small, then new enthalpy $H=h_o$

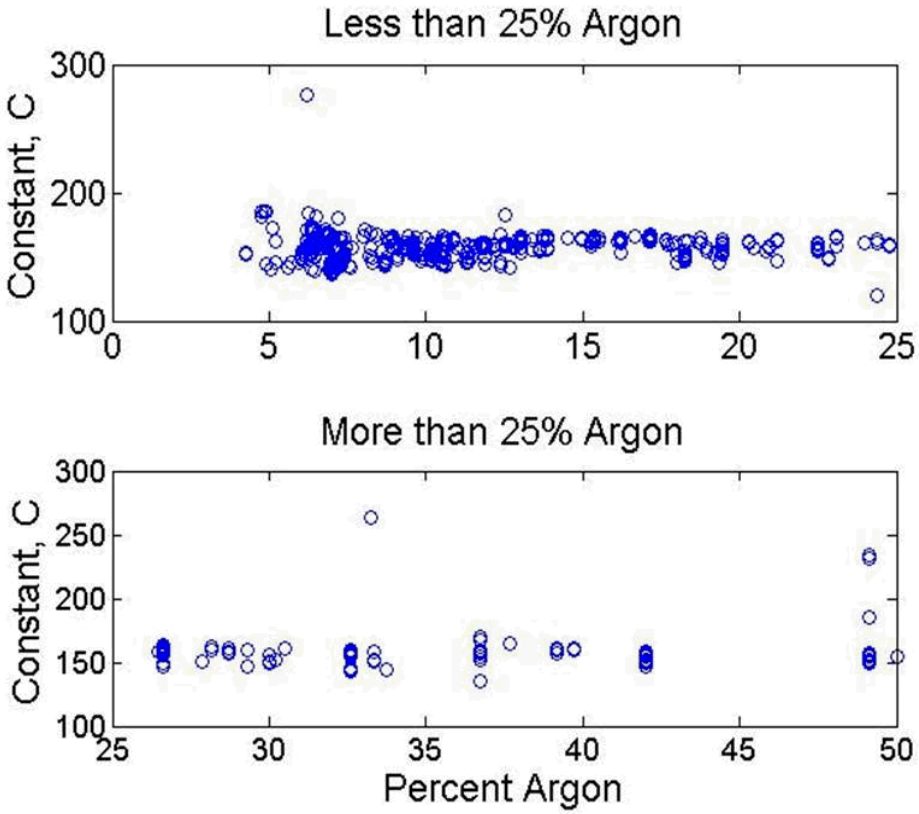
Method

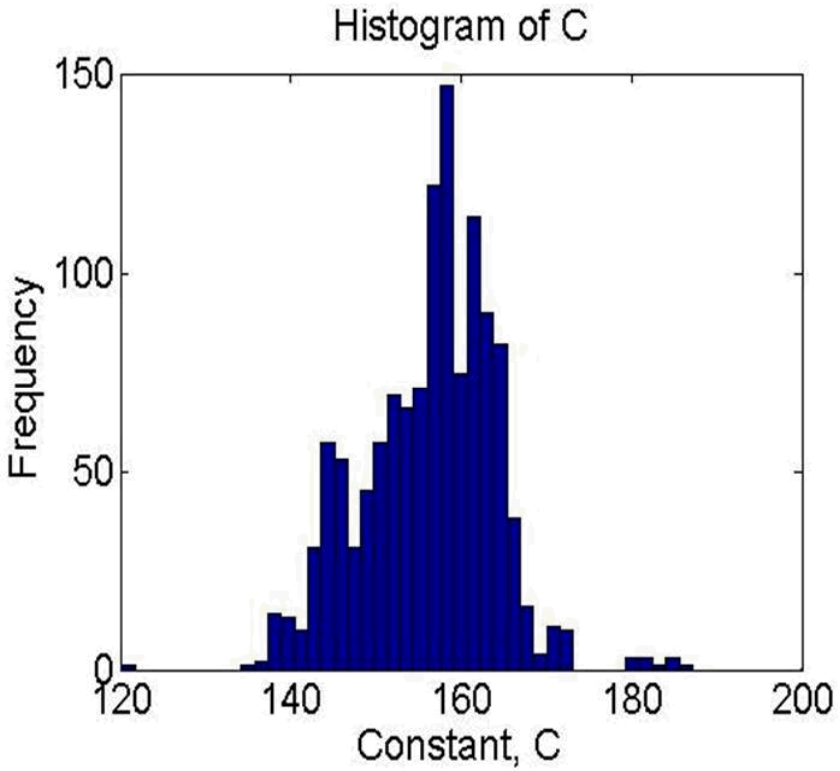

Parameters measured in the Arc Jet and gathered from historical data
P_t, $\dot{m}$, h_t
$P_t = P_o$
Assume Arc Heater
Find the enthalpy value closest to h_t for P_o from table
Find h_o for P_o
Retrieve γ_o and S_o
Retrieve γ_o and S_o for corresponding h_o and P_o from table
If **not** sufficiently small, then guess new h_o
NO
Iterate
Iterate
Calculate P* as a function of P_o and γ_o
$P^*(P_o, \gamma_o)$
Find S^*, a^*, h^*
Select a S* that is closest to S_o at P* and find throat
$U(h_o, h^*)$
Calculate Sonic Velocity
Compare $U(h_o, h^*) - a^* = 0$?
YES
Success
$H_{new} = h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H = h_o$

Method


Parameters measured in the Arc Jet and gathered from historical data
Initial Guessing
P_t, $\dot{m}$, h_t
$P_t = P_o$
Find h_o for P_o
Retrieve γ_o and S_o
Assume Arc Heater pressure and stagnation pressure are equal
Find the enthalpy value closest to h_t for P_o from table
Retrieve γ_o and S_o for corresponding h_o and P_o from table
If **not** sufficiently small, then guess new h_o
Iterate
NO
Calculate P* as a function of P_o and γ_o
Compare $U(h_o,h^*)-a^*=0$?
$U(h_o,h^*)$
Find S^*,a^*,h^*
$P^*(P_o,\gamma_o)$
YES
Calculate Sonic Velocity
Select a S* that is closest to S_o at P* and find throat parameters from table
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$

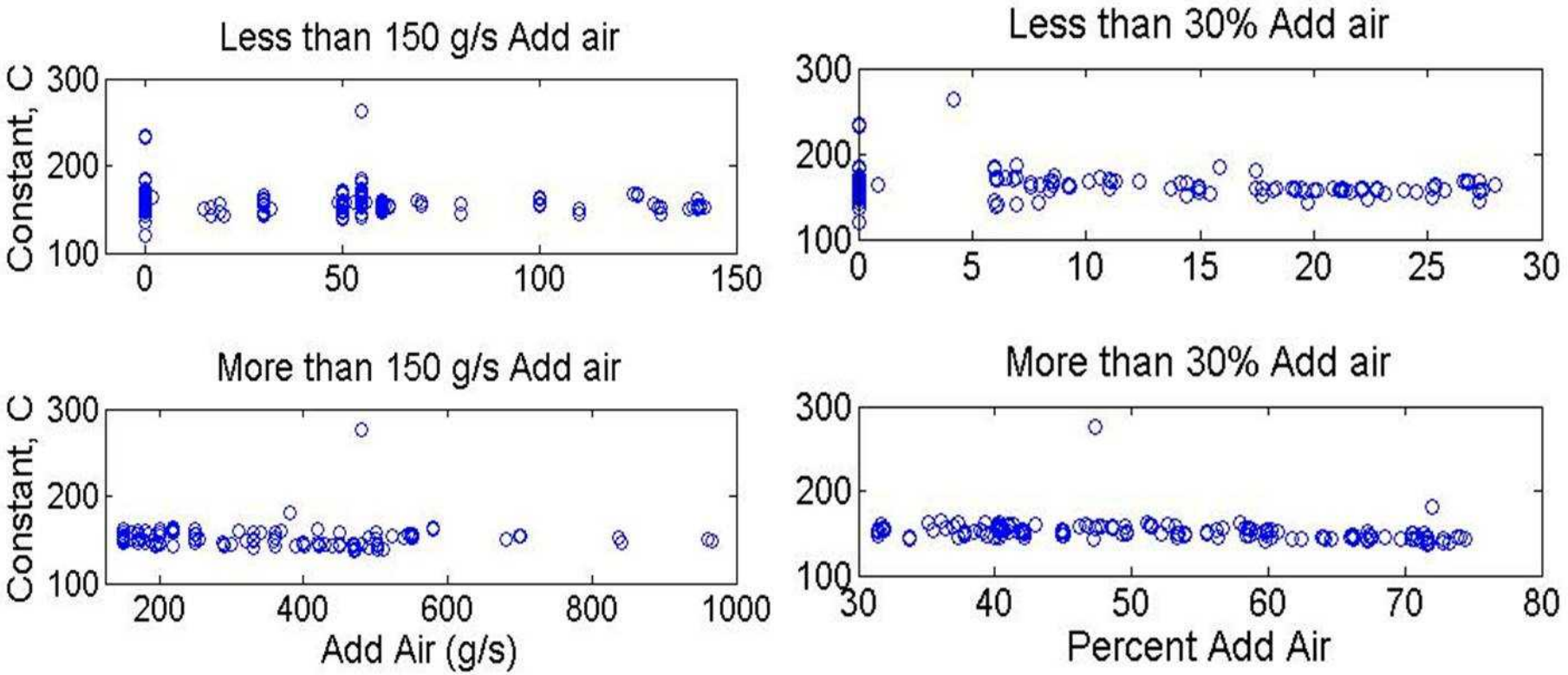
Results: $H_0 = (C/\sigma)^2 \longrightarrow H_0 = (155.8/\sigma)^2$





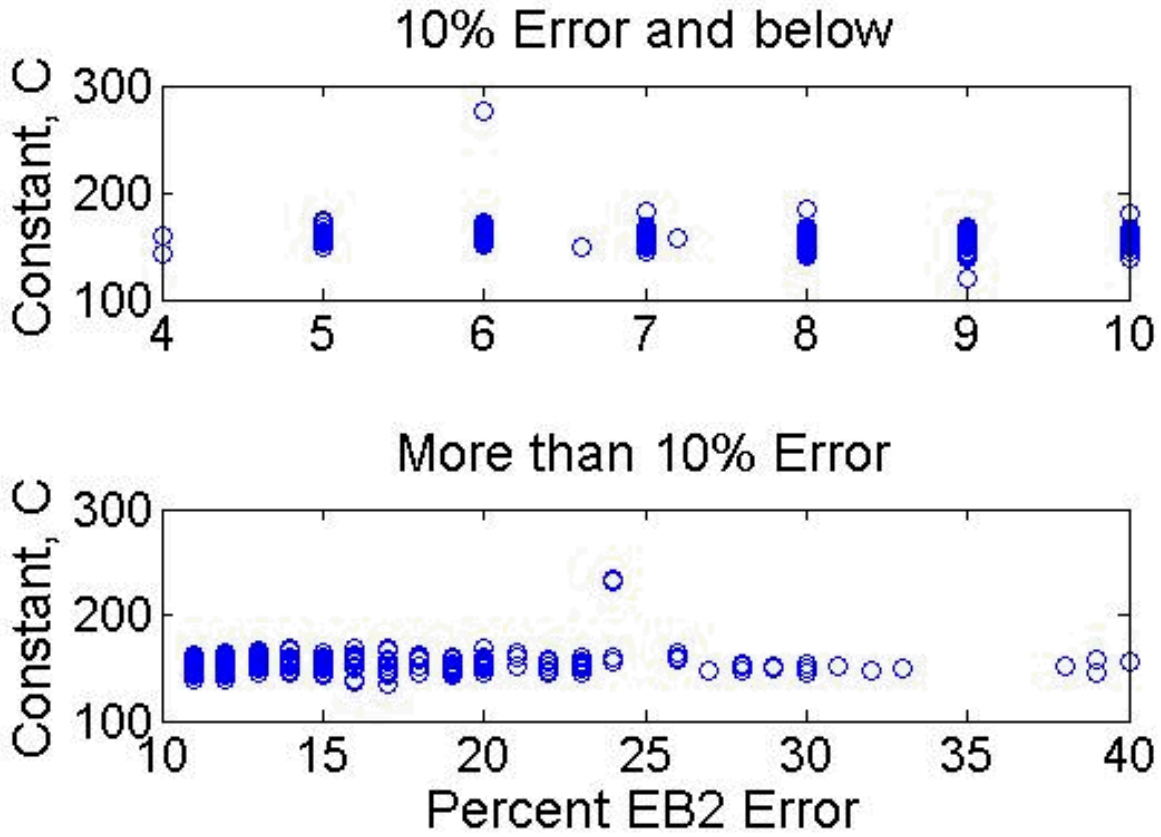
- **The constant, *C*, varies, but not as a function of argon. It approaches a normal distribution.**

Results: $H_0 = (C/\sigma)^2 \longrightarrow H_0 = (155.8/\sigma)^2$



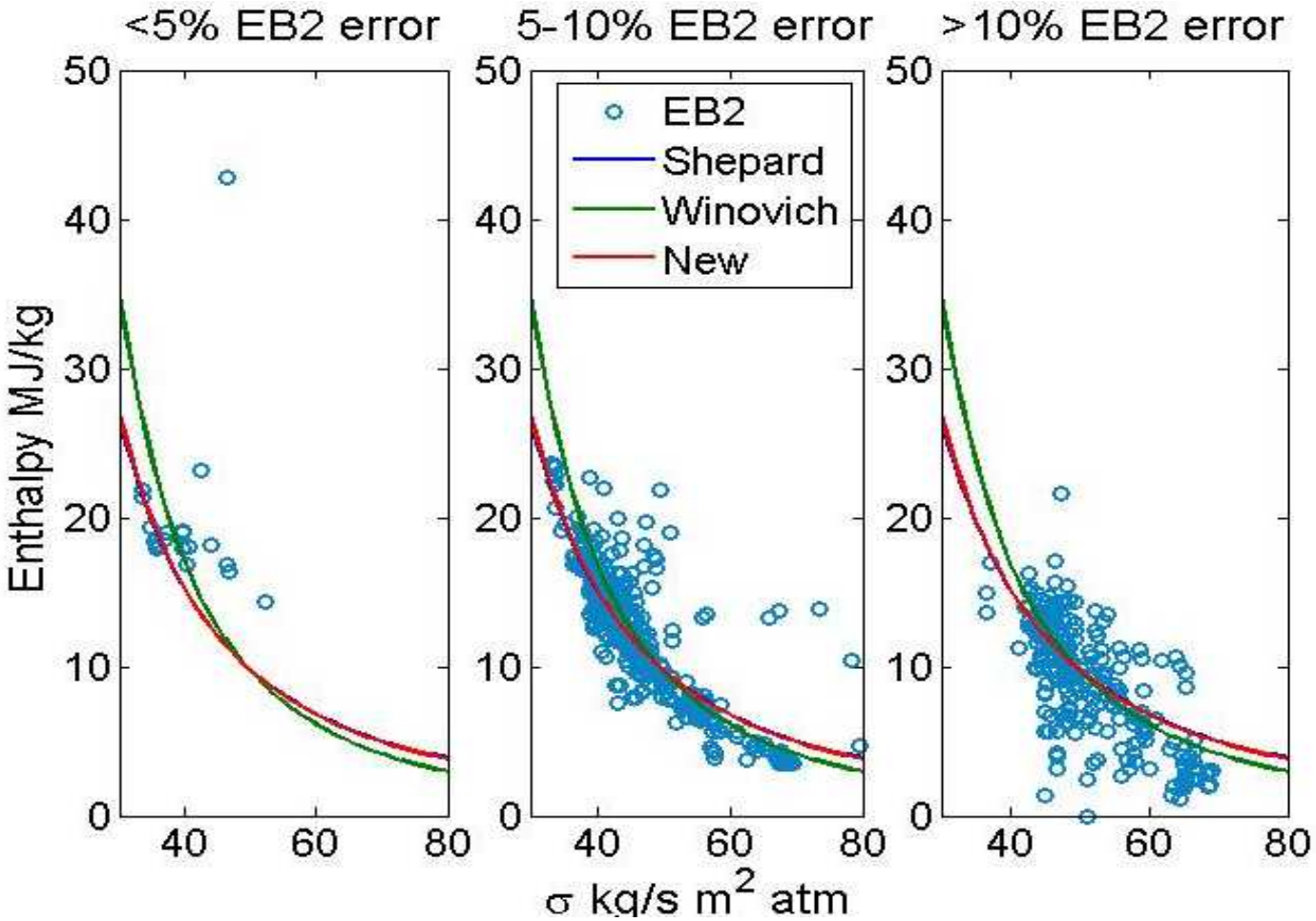
- **The constant, *C*, varies, but not as a function of add air content of flow field (absolute or percent)**

Results: $H_0 = (C/\sigma)^2 \longrightarrow H_0 = (155.8/\sigma)^2$



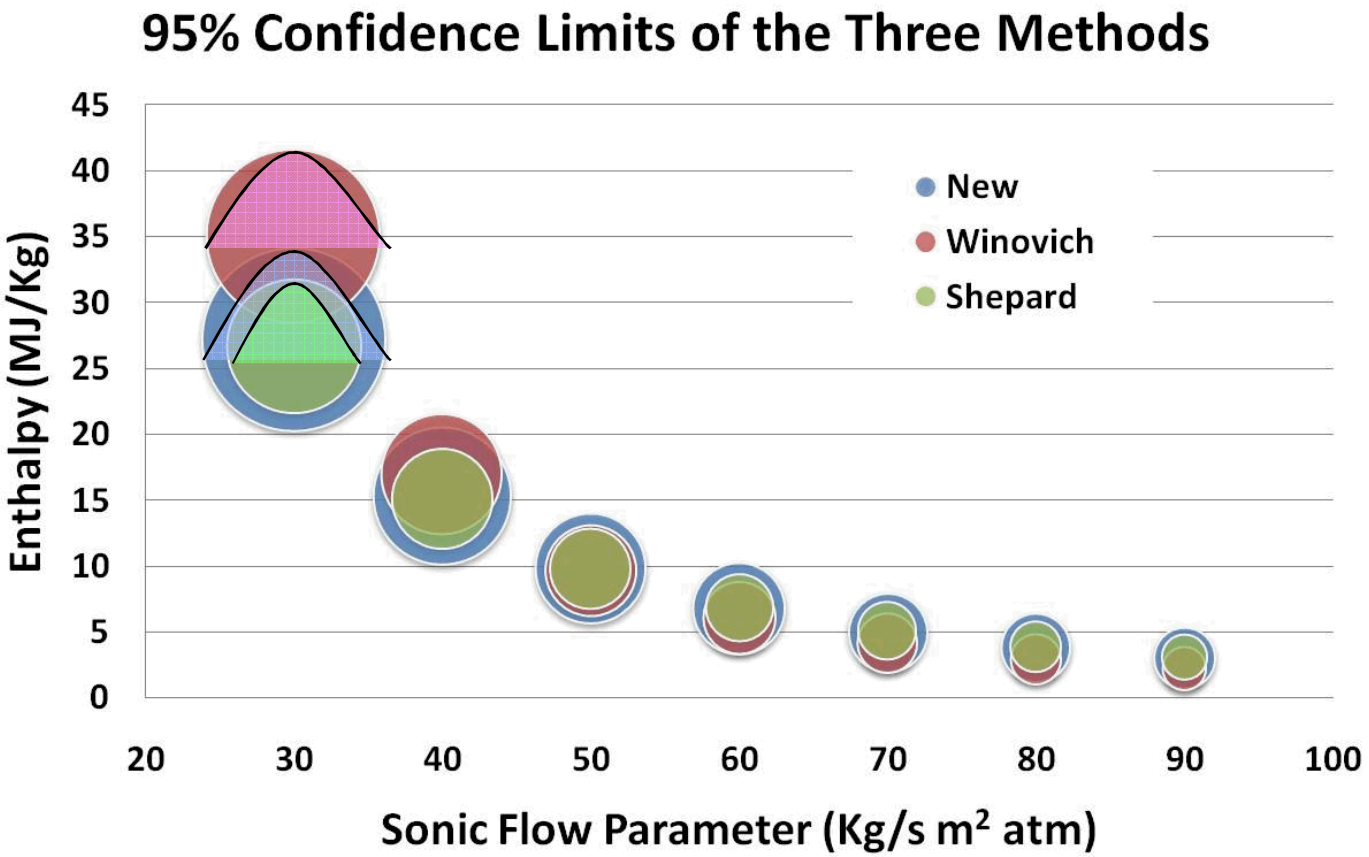
- **The constant, c, does not vary as additional uncertainty is introduced in EB2 calculations**

Results



- **Enthalpy by Energy Balance (EB2) comparison**
- **All methods show similar agreement**

Results



- The three methods are nearly equivalent over large range of σ when confidence is introduced.

Summary and Conclusions

- We can find one value of C and it does not depend on the argon in the flow
  - or the amount of add air, or correlate with EB2 Uncertainty
- The dimensionally correct calculation is at least as accurate as existing calculations
  - compared to EB2 data
- These results apply to the NASA Ames Arc Jet Facilities
  - Applicability to other facilities has not been studied

Questions

Acknowledgements:

Many thanks to the contributors at NASA Ames Research Center for both input and continued support, specifically the Thermophysics Facilities and Aerothermodynamics Branches.

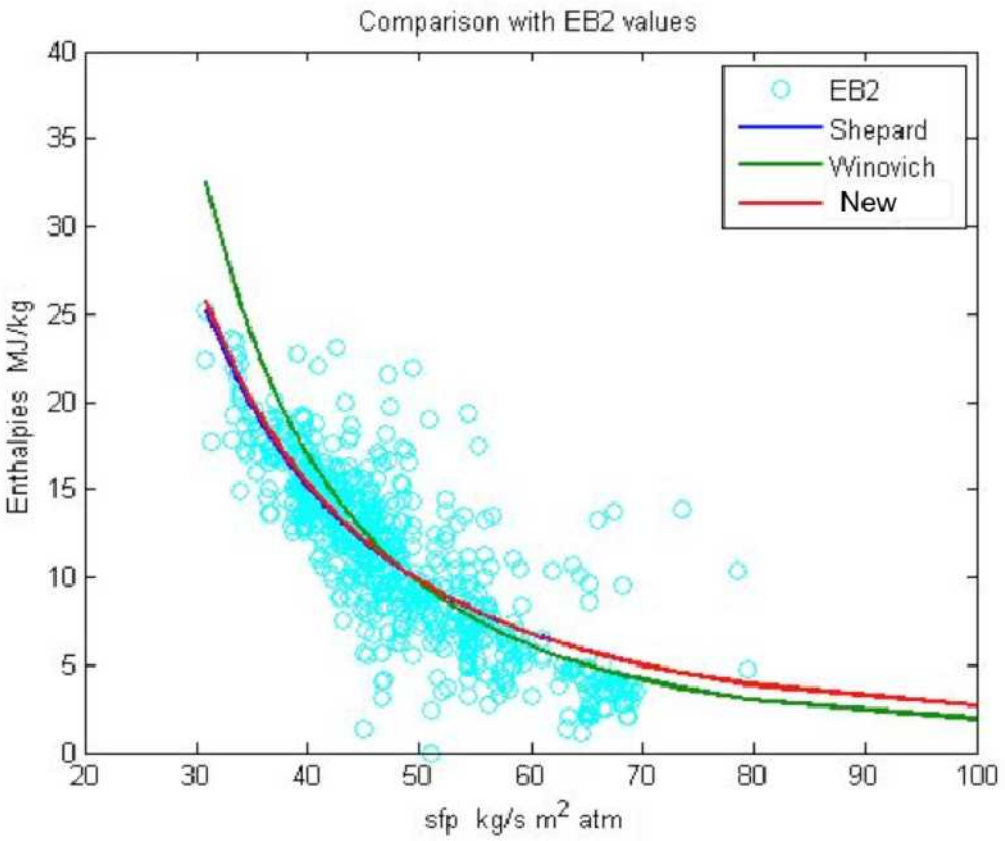
- Dinesh Prabhu--*ERC Inc., NASA Ames Research Center*
- Imelda Terrazas-Salinas--*NASA Ames Research Center*

Thanks also to Sandia National Laboratories center 2600 management for support and encouragement of this work.

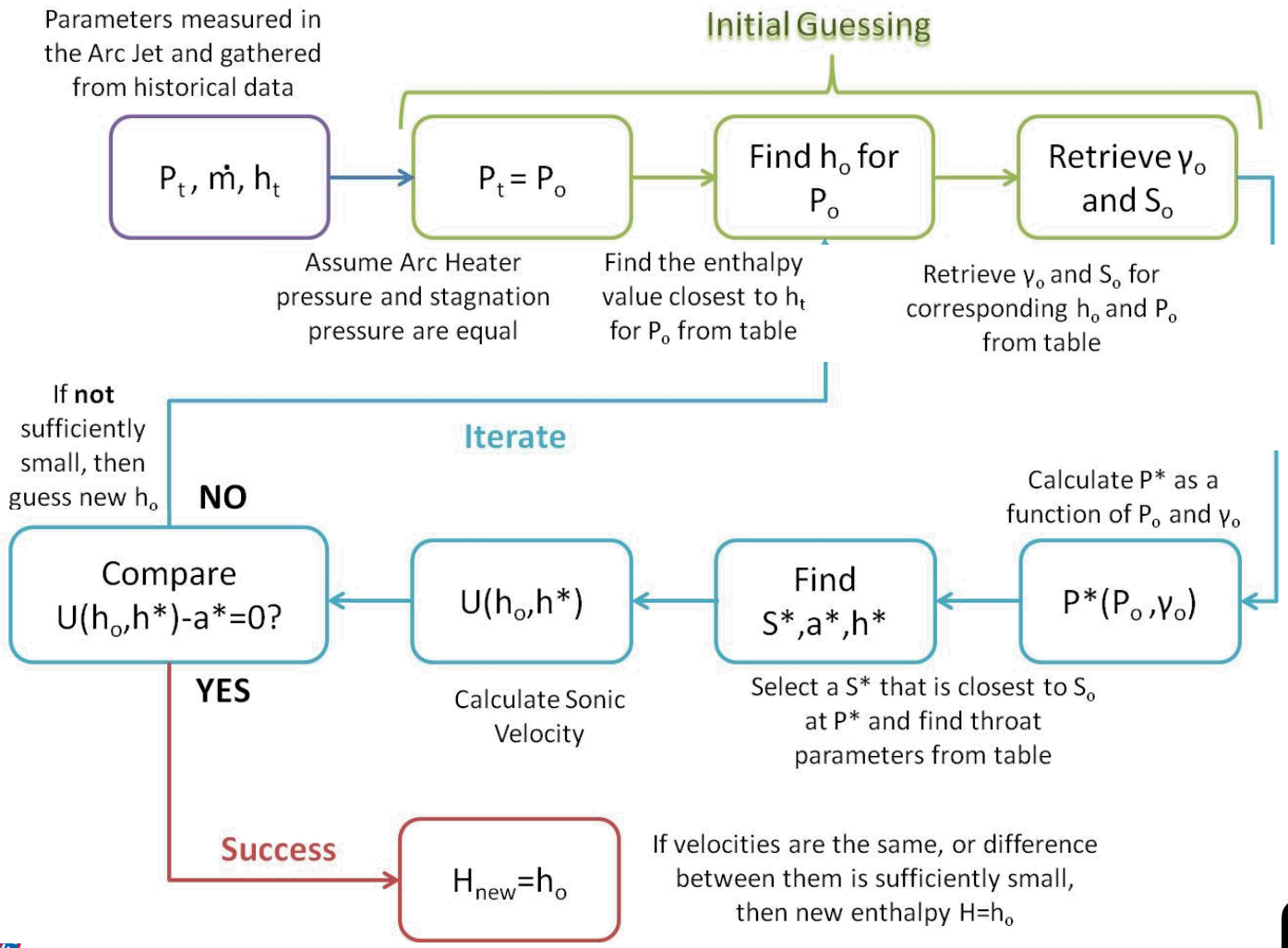
- Hae-Jung Murphy—Sandia National Laboratories

This research was supported by the NASA-SCAP (Strategic Capabilities Assets Program) which provides critical financial support of the arc jet operational capability at NASA Ames Research Center.

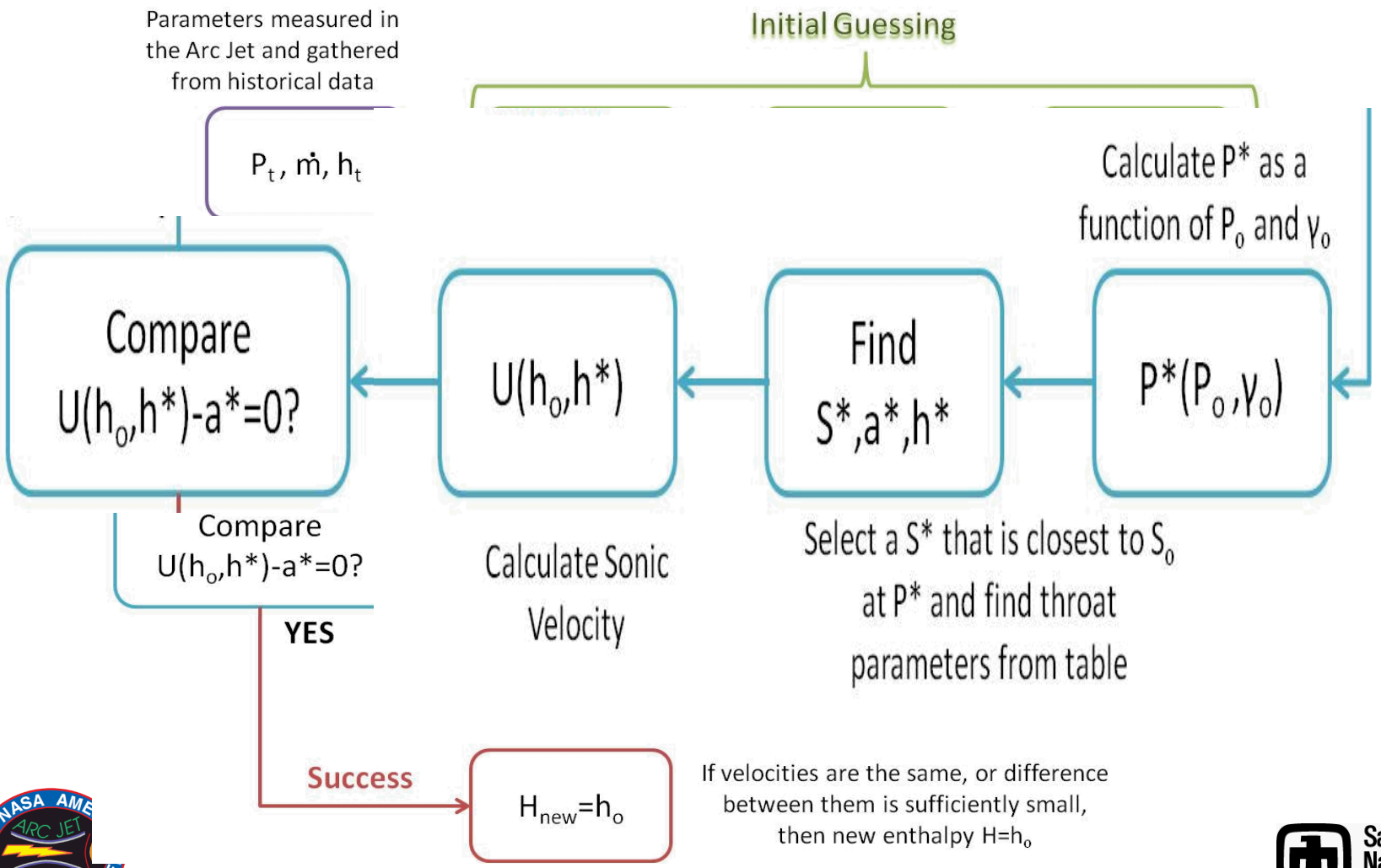
Backup Slides



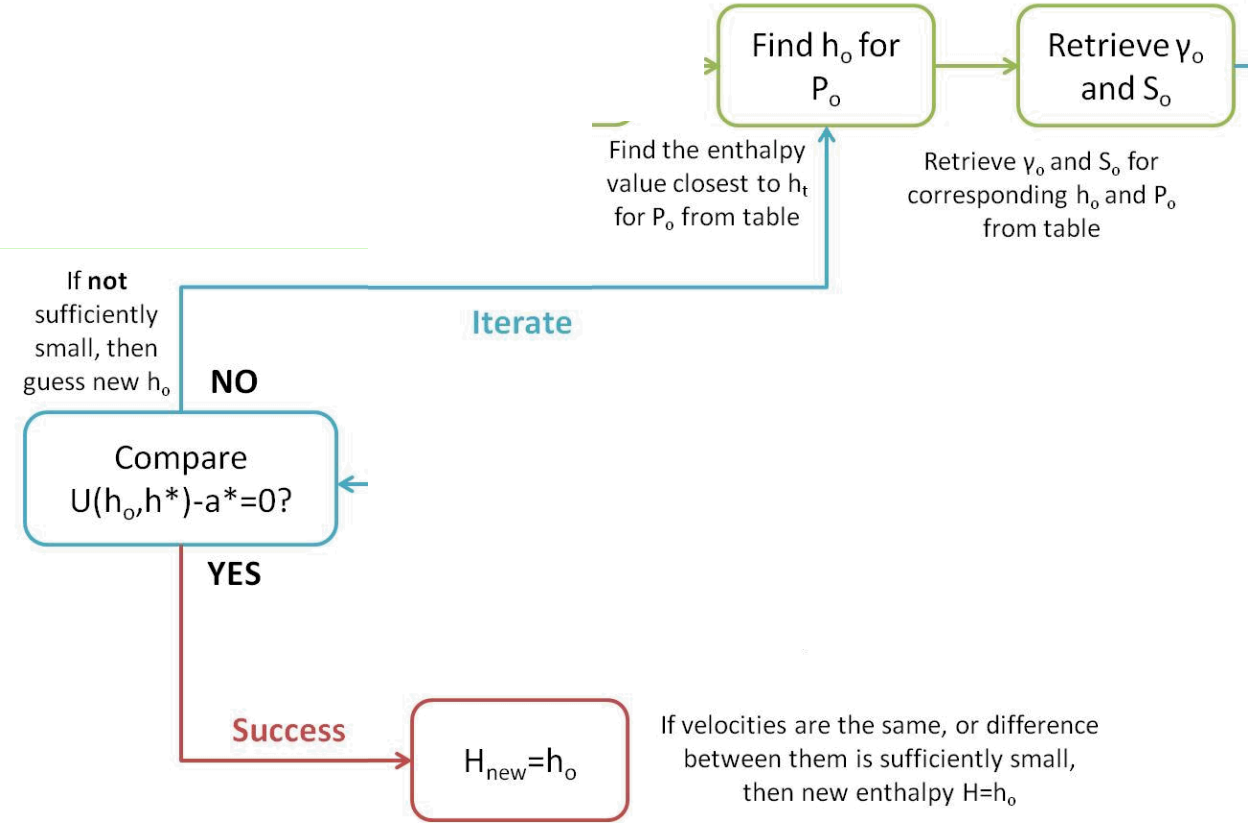
Method


Parameters measured in the Arc Jet and gathered from historical data
Initial Guessing
P_t, $\dot{m}$, h_t
$P_t = P_o$
Find h_o for P_o
Retrieve γ_o and S_o
Assume Arc Heater pressure and stagnation pressure are equal
Find the enthalpy value closest to h_t for P_o from table
Retrieve γ_o and S_o for corresponding h_o and P_o from table
If **not** sufficiently small, then guess new h_o
Iterate
NO
Calculate P* as a function of P_o and γ_o
Compare $U(h_o,h^*)-a^*=0$?
$U(h_o,h^*)$
Find S^*,a^*,h^*
$P^*(P_o,\gamma_o)$
YES
Calculate Sonic Velocity
Select a S* that is closest to S_o at P* and find throat parameters from table
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$

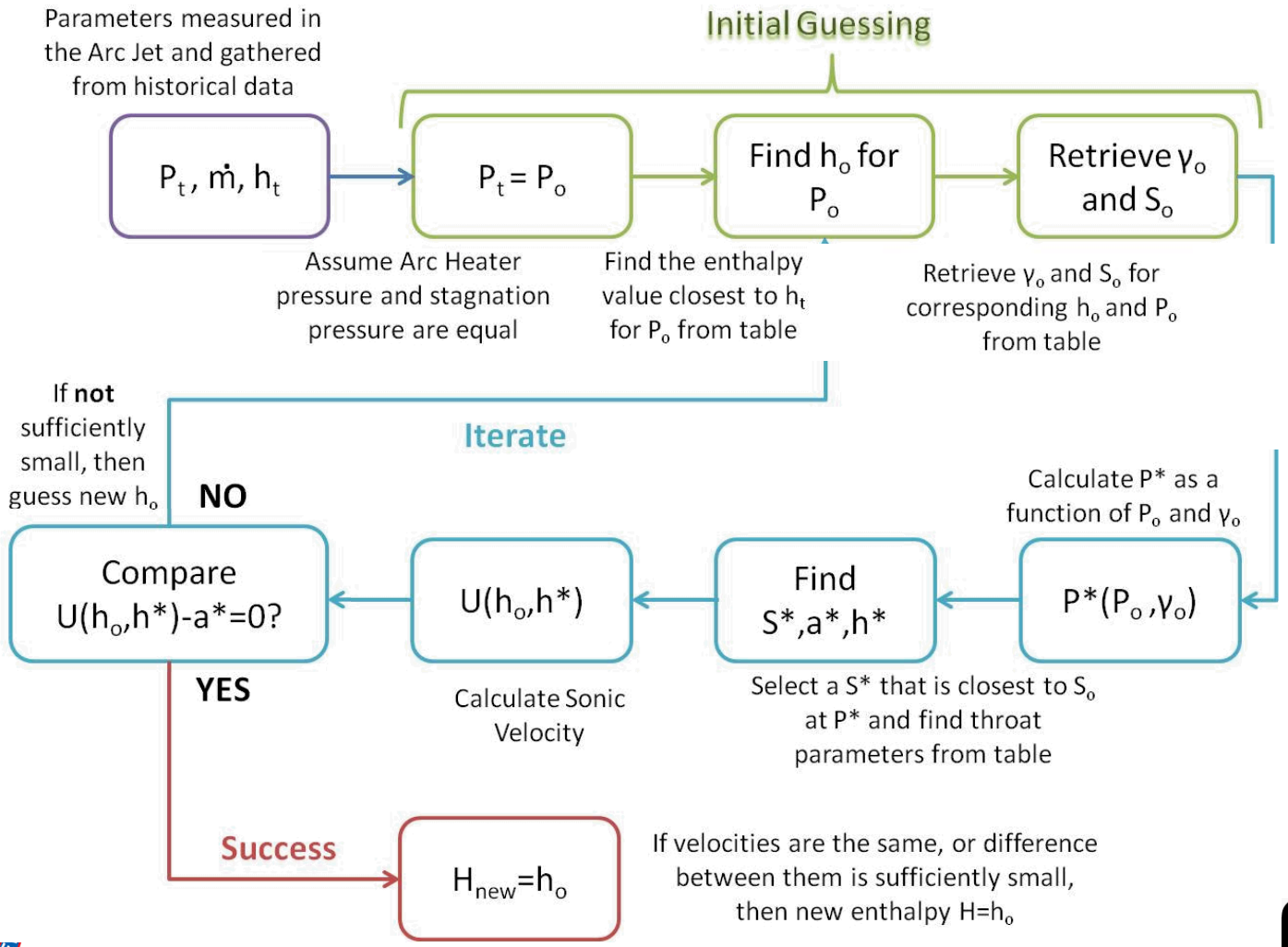
Method


Parameters measured in the Arc Jet and gathered from historical data
Initial Guessing
P_t, $\dot{m}$, h_t
Calculate P* as a function of P_o and γ_o
Compare $U(h_o,h^*)-a^*=0$?
$U(h_o,h^*)$
Find S^*,a^*,h^*
$P^*(P_o,\gamma_o)$
Compare $U(h_o,h^*)-a^*=0$?
Calculate Sonic Velocity
Select a S* that is closest to S_o at P* and find throat parameters from table
YES
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$

Method


Find h_o for P_o
Retrieve γ_o and S_o
Find the enthalpy value closest to h_t for P_o from table
Retrieve γ_o and S_o for corresponding h_o and P_o from table
If **not** sufficiently small, then guess new h_o
Iterate
NO
Compare $U(h_o,h^*)-a^*=0$?
YES
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$

Method


Parameters measured in the Arc Jet and gathered from historical data
Initial Guessing
P_t, $\dot{m}$, h_t
$P_t = P_o$
Find h_o for P_o
Retrieve γ_o and S_o
Assume Arc Heater pressure and stagnation pressure are equal
Find the enthalpy value closest to h_t for P_o from table
Retrieve γ_o and S_o for corresponding h_o and P_o from table
If **not** sufficiently small, then guess new h_o
Iterate
NO
Calculate P* as a function of P_o and γ_o
Compare $U(h_o,h^*)-a^*=0$?
$U(h_o,h^*)$
Find S^*,a^*,h^*
$P^*(P_o,\gamma_o)$
YES
Calculate Sonic Velocity
Select a S* that is closest to S_o at P* and find throat parameters from table
Success
$H_{new}=h_o$
If velocities are the same, or difference between them is sufficiently small, then new enthalpy $H=h_o$