Thermal Management for Aircraft

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Outline

- **Description of thermal management issues**

- **Two areas of research**

  - **Fuel Thermal Management**
    - **Fuel acts as a thermal capacitor to store thermal energy**
    - **Develop topologies & control laws to increase thermal endurance**

  - **Electromechanical Actuation System**
    - **Innovative actuator & control allocation**

Thermal Management Problem Statement and Objectives

"Thermal considerations can potentially limit the operating performance, and even the practical feasibility of many key capabilities that the Air Force will need to accomplish its future mission[1]."

Problem:

- **Reduced ability of aircraft to transfer heat to atmosphere (composite skins, fewer air intake ports)**
- **Heat generating systems (sensors, EMAs, electronic attack systems, etc)**
- **Fuel can exceed temperature limit prior to completion of mission**
    - **Fuel coking, reduced performance, subsystem failure, vehicle failure**

[1] Scientific Advisory Board, U. S. A. F., "Thermal Management Technology Solutions, Vol. 1," Tech. Rep. SAB-TR-07-05, Air Force, 2007

Objective: Extend Thermal Endurance of Aircraft

- **Use fuel as thermal capacitor: thermal energy injected into atmosphere by engine**
- **Develop control oriented physics based models of aircraft thermal behavior**
- **Develop methods that can rapidly estimate aircraft thermal behavior through analytical results**
- **Reduction of heat loads due to actuation system**

Thermal Endurance

Aircraft Endurance

- **Amount of time aircraft can operate until all fuel is expended**

Thermal Endurance (when fuel is used as heat sink to manage temperature)

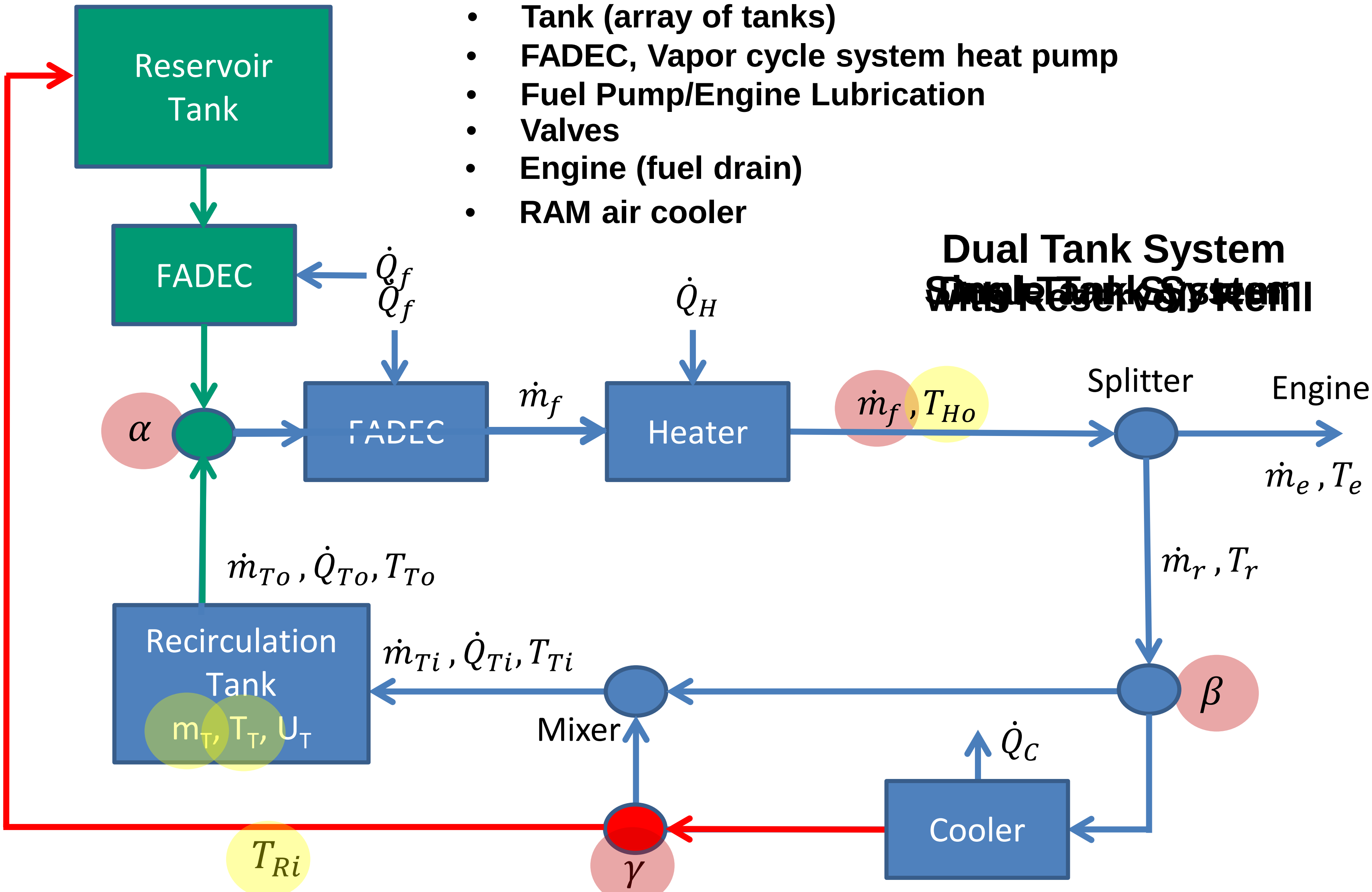
- **Amount of time aircraft can operate until fuel exceeds a temperature limit**

- **Past methods for approaching aircraft thermal management issues**
  - **Improve efficiency of subsystems**
  - **Create detailed simulations of aircraft thermal performance**

- **This work has a different approach**
  - **Develop transparent physical models of complex thermal system behavior**
  - **Investigate new fuel flow topologies**
  - **Develop control laws to increase thermal endurance**
  - **New actuator concept to reduce thermal loads**

Fuel Thermal Management Topologies

- Tank (array of tanks)
- FADEC, Vapor cycle system heat pump
- Fuel Pump/Engine Lubrication
- Valves
- Engine (fuel drain)
- RAM air cooler

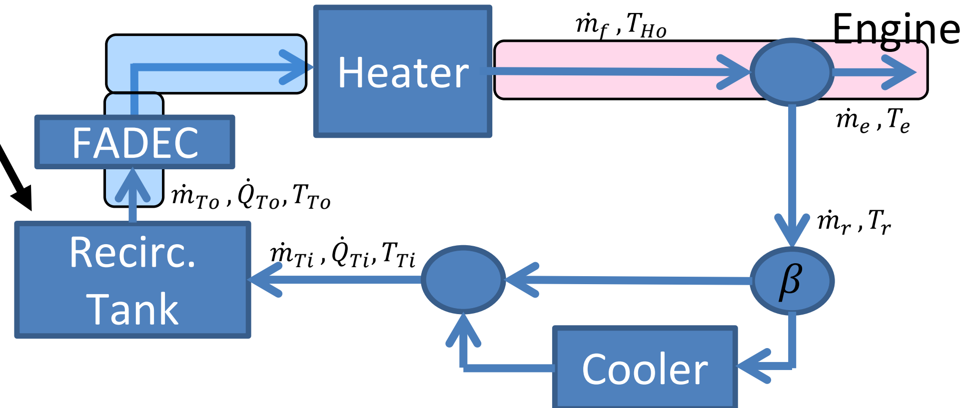


Why Dual vs. Single Tank?

- **To improve thermal endurance, eject maximum amount of thermal energy to atmosphere via engine**

Fighter
≈ 3000 kg

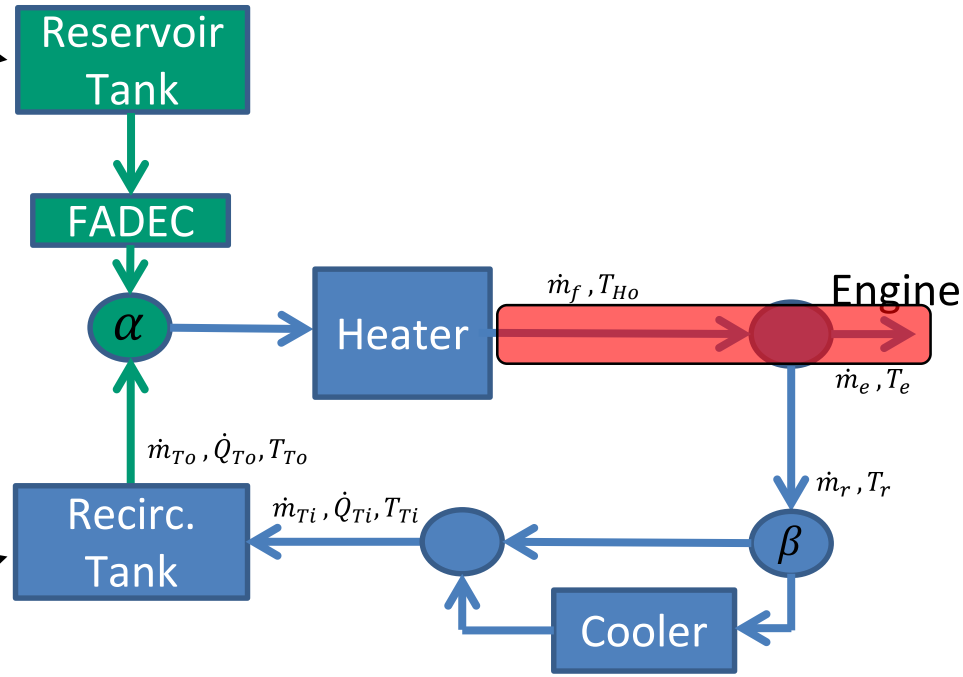
- **Single tank topology: large mass in tank requires significant time to achieve desired temperature**
- **Low thermal energy is ejected during this period**



≈ 2800 kg

- **Dual tank: Tank contains small mass**
- **Can be heated quickly**
- **Yields maximum temp. fuel**
- **High thermal energy ejected into atmosphere**
- **Allows cool and hot fuel to be mixed later in flight (avoids violation of FADEC temp. limit)**

≈ 200 kg



Thermal Modeling

Internal Energy of Tank $U_T = m_T c_v (T_T - T_r) \Longrightarrow \frac{dU_T}{dt} = \dot{m}_T c_v (T_T - T_r) + m_T c_v \dot{T}_T$

ODEs describing time evolution of tank temperature

Tank Thermal Energy = Thermal E

$$\frac{dU_T}{dt} = \dot{m}_{T_i} c_v (T_{T_i} - T_r) - \dot{m}_{T_o} c_v (T_T - T_r)$$

$$\dot{T}_{1_S} = \left(\frac{\dot{m}_f - \dot{m}_e}{m_{1_S}}\right)\left[\left(e^U - 1\right)(T_1 - T_w) + e^U \left(\frac{\dot{Q}_h + \dot{Q}_f}{\dot{m}_f c_v}\right)\right]$$

$$\dot{T}_{1_D} = \left(\frac{\dot{m}_f - \dot{m}_e}{m_{1_D}}\right)(1-\alpha)(T_2 - T_1) + \frac{1}{m_{1_D} c_v}\left(\frac{\dot{m}_f - \dot{m}_e}{\dot{m}_f}\right)\left(\dot{Q}_h + \dot{Q}_f\right)$$
$$-\beta\left(\frac{\dot{m}_f - \dot{m}_e}{m_{1_D}}\right)\left(1 - e^{\frac{U}{\beta}}\right)\left(\alpha T_1 + (1-\alpha) T_2 - T_w + \frac{\dot{Q}_h + \dot{Q}_f}{\dot{m}_f c_v}\right)$$

$$T_{C_o} = T_w + e^{\frac{-U_C A_C}{\dot{m}_{C_i} c_v}} (T \ldots$$

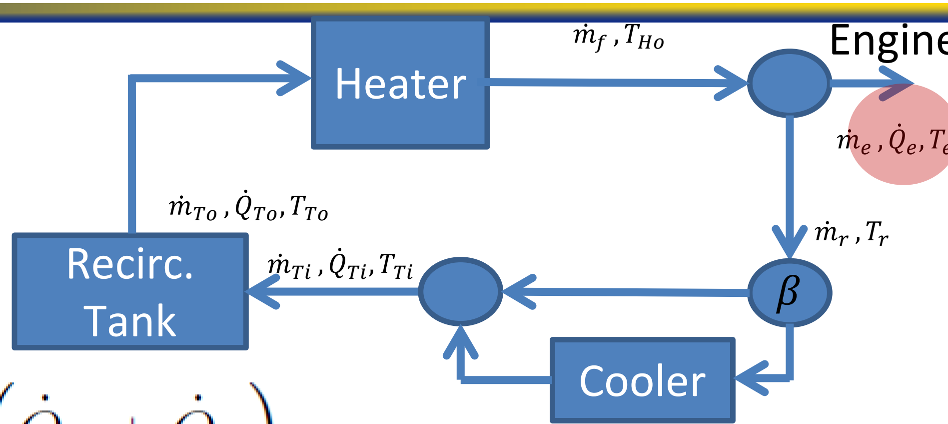
$\dot{Q}_C$

$\dot{Q}_H$

$$\dot{m}_{1_S} = -\dot{m}_e$$

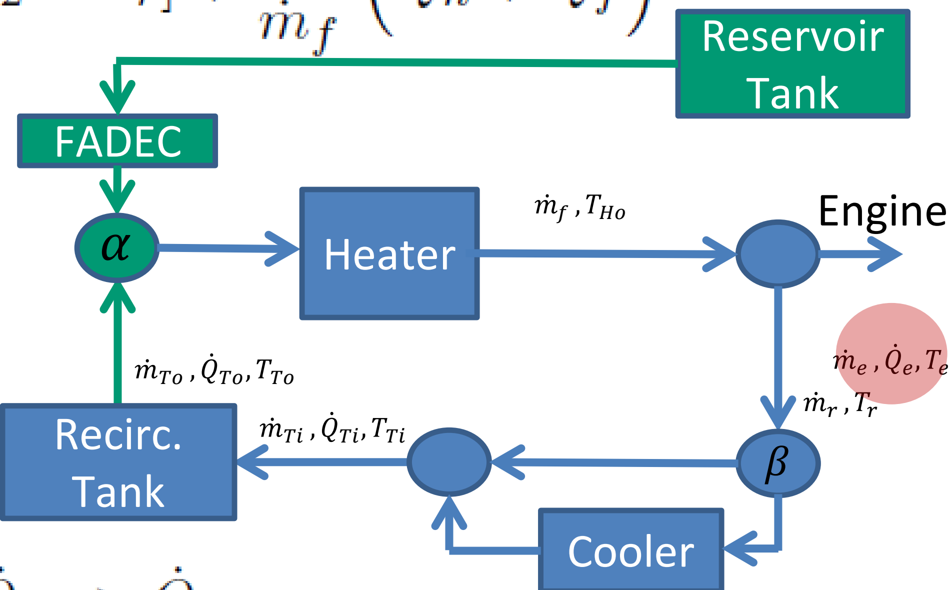
$$\dot{m}_{1_D} = (1-\alpha)\,\dot{m}_f - \dot{m}_e$$

Dual Tank vs. Single Tank Energy Disposal Rate Through Engine



$$\dot{Q}_{e_S}(t) = \dot{m}_e c_v \left(T_{1_S}(t) - T_r\right) + \frac{\dot{m}_e}{\dot{m}_f}\left(\dot{Q}_h + \dot{Q}_f\right)$$

$$\dot{Q}_{e_D}(t) = \dot{m}_e c_v \left[\alpha T_{1_D}(t) + (1-\alpha) T_2 - T_r\right] + \frac{\dot{m}_e}{\dot{m}_f}\left(\dot{Q}_h + \dot{Q}_f\right)$$



$$\alpha T_{1_D}(t) + (1-\alpha) T_2 > T_{1_S}(t) \quad \Rightarrow \quad \dot{Q}_{e_D} > \dot{Q}_{e_S}$$

Theorems

Theorem If $T_{1_f} > \bar{T}_1 > 0$, $m_{1_S}(0) > m_1(0)$, $\dot{m}_f > \dot{m}_e$, then the thermal endurance of a dual tank system will exceed that of a single tank system, i.e., $t_D > t_S$.

$$t_D - t_S = \frac{m_{1_S}(0) - m_1(0)}{\dot{m}_e}\left[\frac{\bar{T}_1 - T_{1_f}}{T_1(0) - T_{1_f}}\right]^{\frac{-\dot{m}_e}{\eta S}} \Rightarrow t_D > t_S$$

>0 >0 0-1 >0

Corallary Maximum improvement in thermal endurance is achieved when the initial recirculation tank fuel mass in a dual tank systems is zero, i.e., $m_1(0) = 0$.

$$t_D - t_S = \frac{m_{1_S}(0) - m_1(0)}{\dot{m}_e}\left[\frac{\bar{T}_1 - T_{1_f}}{T_1(0) - T_{1_f}}\right]^{\frac{-\dot{m}_e}{\eta S}}$$

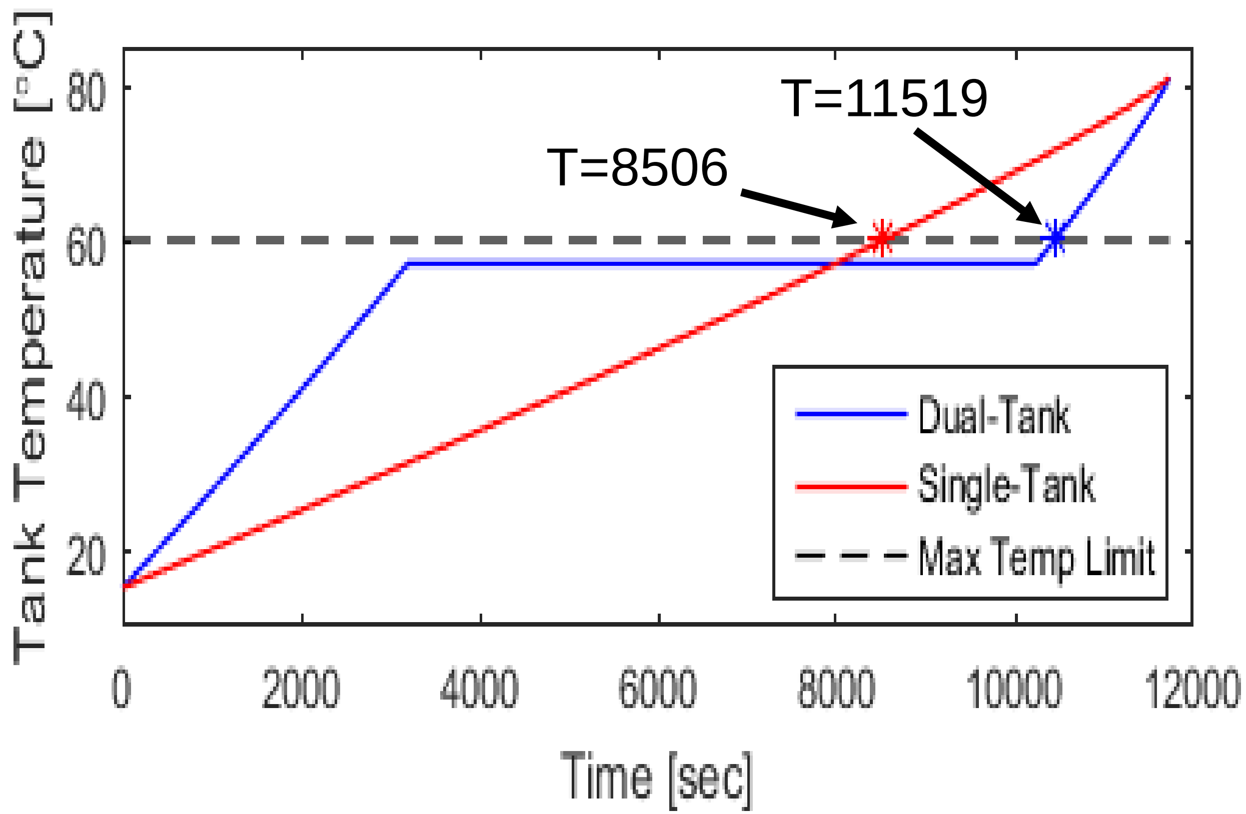
>0 <0 >0

As recirculation tank mass goes to zero, max thermal endurance is achieved

Dual Tank Simulation Results

- **Single tank fails before completion of the mission**
- **Dual tank completes the mission with a (near) empty tank**

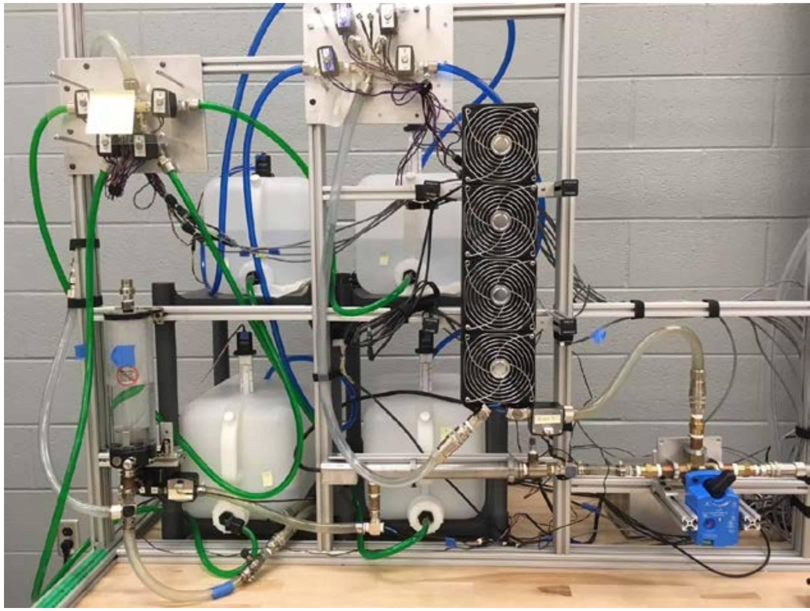
Parameter	Value	Units
$m_{1_S}(0)$	3050	kg
$m_1(0)$	200	kg
$m_2(0)$	2850	kg
$\dot{m}_f$	1	kg/s
$\dot{m}_e$	0.26	kg/s
$T_{1_S}(0) = T_1(0) = T_2(t)$	288	K
$\overline{T_1}$	333	K
$U_c A_c$	550	W/K
T_w	238	K
r	0.8	-
$\dot{Q}_{h_v}$	59000	W
$\dot{Q}_{h_e}$	10000	W
$\dot{Q}_F$	1000	W
P_p	50000	W
η_r	0.5	-
η_ω	0.9	-
c_v	2010	J/(kg-K)



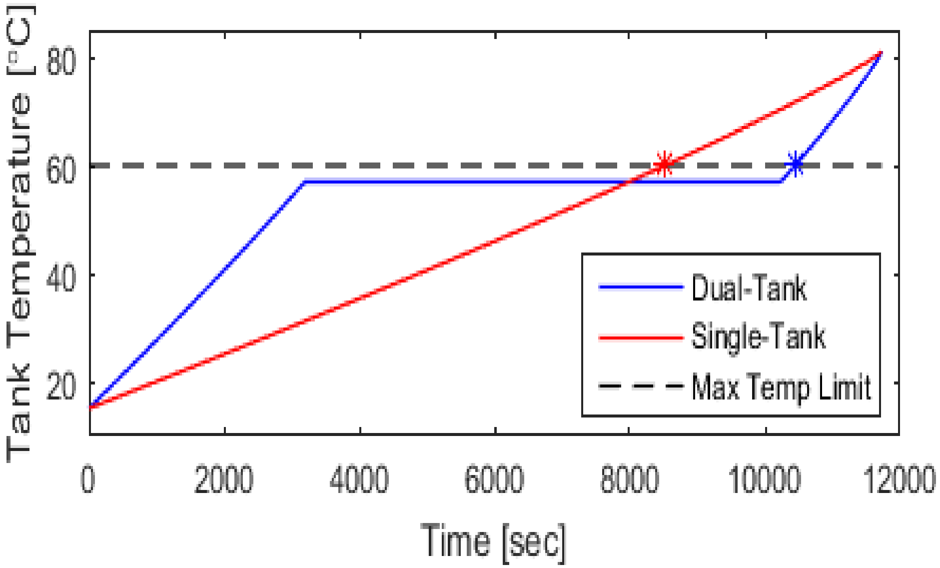
- **Pros: 35% increase in thermal endurance**
- **Cons: Added alpha valve, second tank, additional piping**

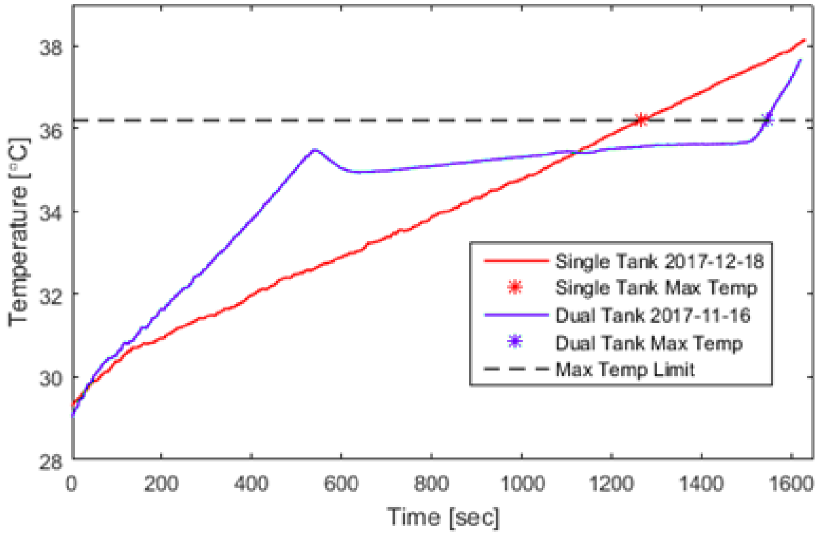
Scaled Water Experiment (Work in Progress)

- **Validation of full scale simulation results**
- **Small scale water experiment**
- **Dynamic similitude via Buckingham Pi Theorem**
- **Equivalence of dimensionless parameters ensures dynamic similarity**



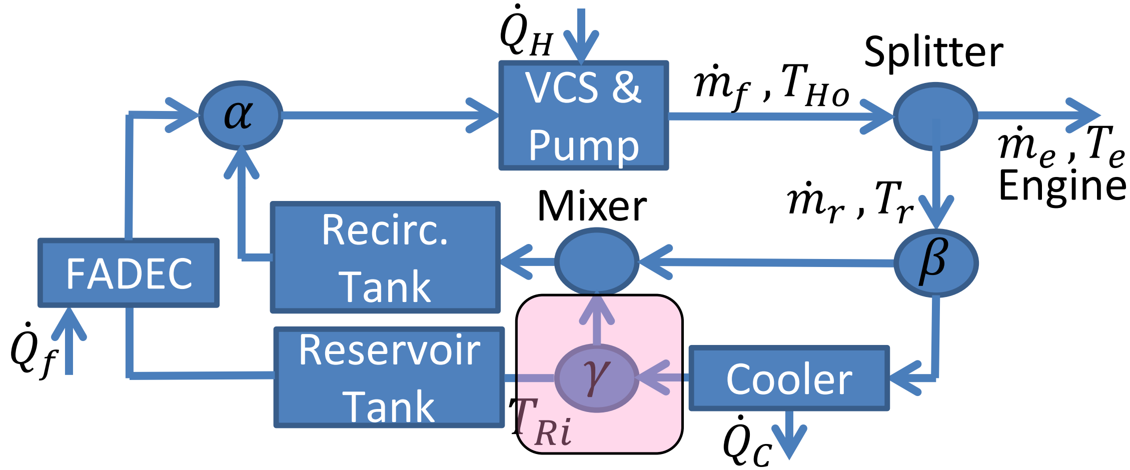
Variable	Full-scale Fuel	Sub-scale Water
Tank Temp Range	$58°F - 220°F$	$58°F - 107°F$
Wall Temp	$-31°F$	$32°F$
m_0	3050 kg	19 kg
c_v	2010 J/(kg-K)	4186 J/(kg-K)





Fuel Thermal Management Topologies With Online Temperature Regulation

Dual Tank System with Reservoir Refill



Dual Tank Configuration

- Reservoir tank temperature is used as a reference temperature
- Reservoir tank temperature is constant
- Recirculation tank temperature and level regulated, arbitrary low value
- Net-onboard thermal energy regulated to an arbitrarily small positive value

Configuration Valve Improvement

- When nominal flow from the cooler is colder than the reference temperature, siphon that flow to the reservoir tank
- When possible, drive the net-onboard thermal energy negative
- Allowing greater thermal endurance if mission parameters change

Outline

- Thermal management issue
  - What cause the issues
  - How can we overcome

- Two areas of research

  - Fuel Thermal Management
    - Fuel acts as a thermal capacitor to store thermal energy
    - Develop topologies & control laws to increase thermal endurance

  - Electromechanical Actuation System
    - Innovative actuator developed

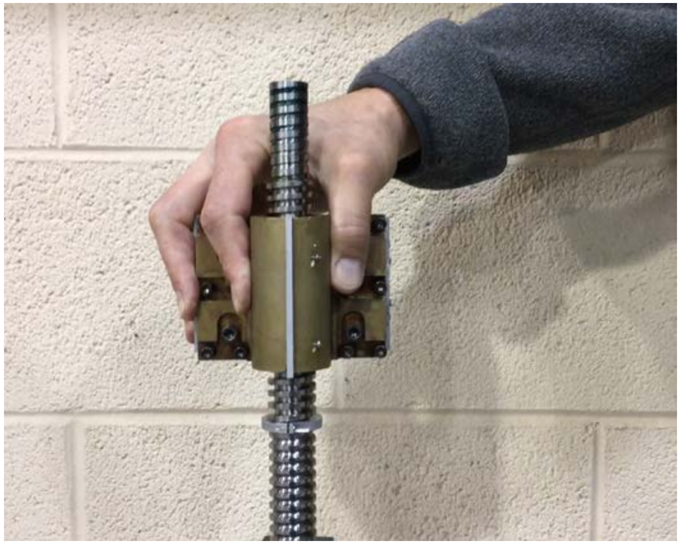
Selectively Self Locking Actuator

- Aircraft actuation systems contribute to high thermal loads
- Minimize waste thermal energy = minimize motor torque (current)

State of the art: Backdriveable Screw

Motor current (torque) required to hold a load

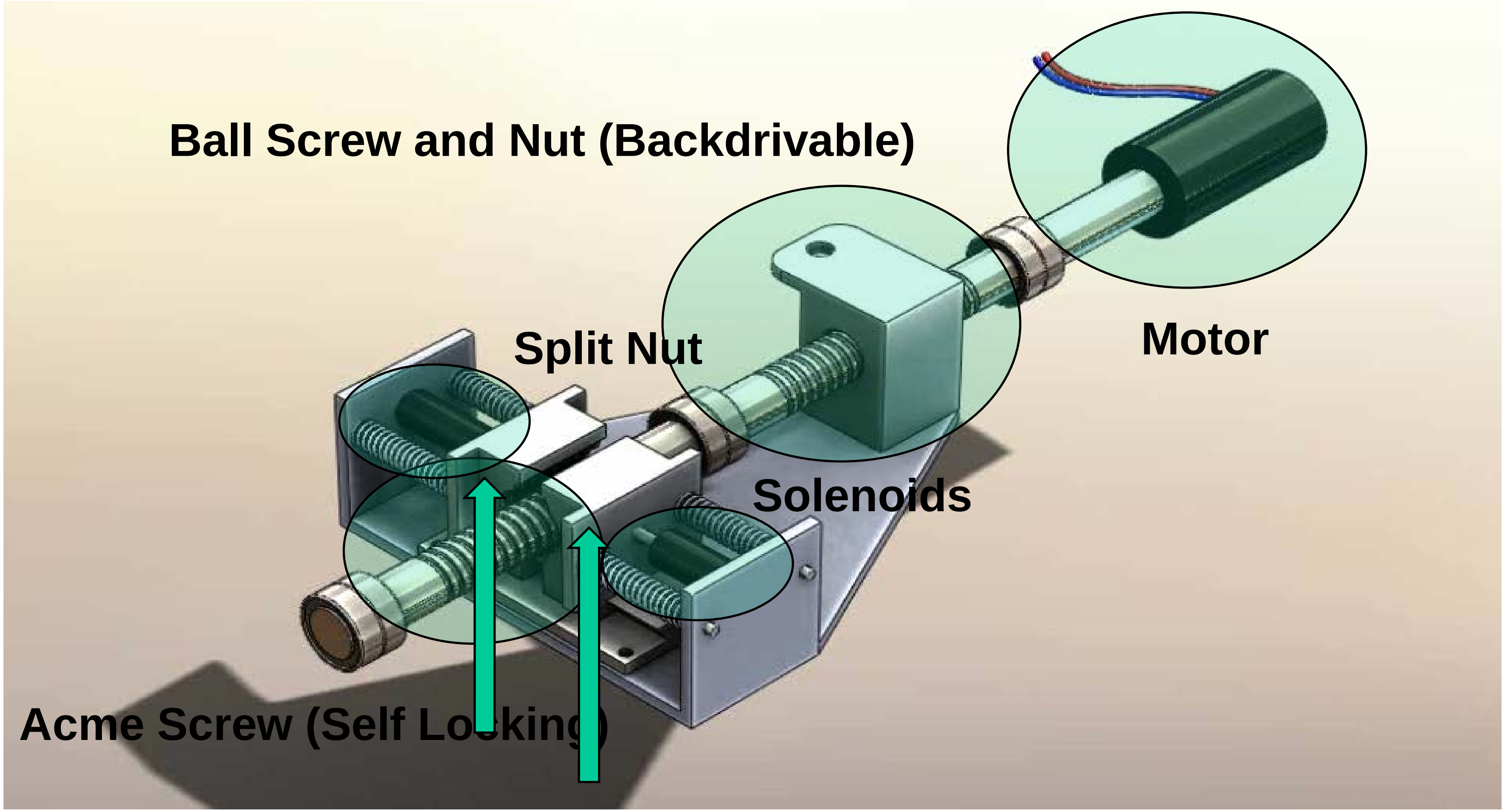
Self Locking Screw



Motor current (torque) NOT required to hold a load (i.e., automotive scissor jack)

Objective: Develop new actuator concept that is failsafe and can hold loads with no motor current

Selectively Self Locking Actuator (cont.)



Thermal Load Minimization

EMA

Experimental Setup

- Couple this EMA concept with a modification to conventional control allocation
- Typical ... norm deflecti...
- Modify this to minimize the change in control surface deflection (hold constant)

$$\min_{\delta} J = \min_{\delta} \left(\| \mathrm{B}\delta - \mathrm{d_{des}} \|_1 + \lambda \| \mathrm{W}(\delta - \delta_{\mathrm{p}}) \|_1 \right)$$

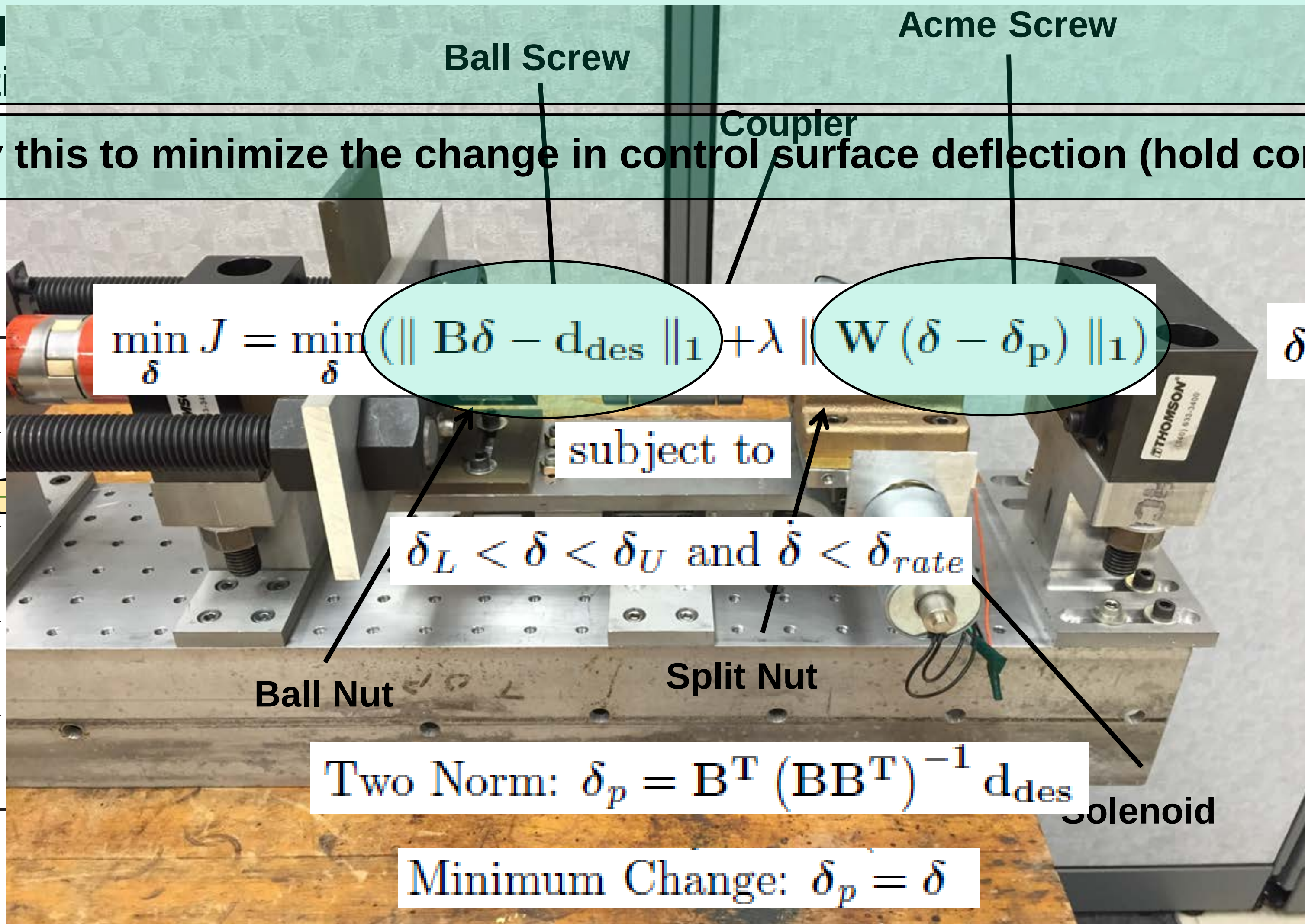
$$\delta \in \mathbb{R}^m$$

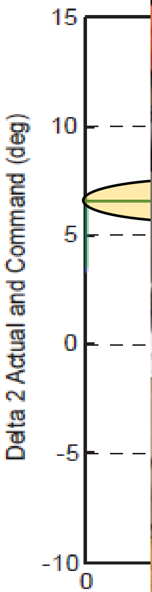
subject to

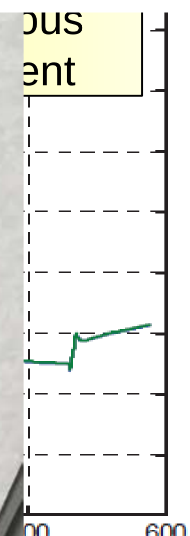
$$\delta_L < \delta < \delta_U \text{ and } \dot{\delta} < \delta_{rate}$$

$$\text{Two Norm: } \delta_p = \mathrm{B^T} \left(\mathrm{BB^T} \right)^{-1} \mathrm{d_{des}}$$

$$\text{Minimum Change: } \delta_p = \delta$$







Publications

Publications: 3 Journal and 10 Conference papers, 2 US Patent Applications

Selected Publications:

- David B. Doman, "Fuel Flow Topology for Extending Aircraft Thermal Endurance," Journal of Thermophysics and Heat Transfer, Vol. 32, No.1, Jan. 2018
- D. Doman, M. Oppenheimer, W. Rone, "Selective Self-Locking Actuator and Control Allocation Approach for Thermal Load Minimization," AIAA Journal of Guidance, Control, and Dynamics, Vol. 38, No. 6, June 2015
- Michael W. Oppenheimer, David O. Sigthorsson, and David B. Doman, "Control of Fuel Thermal Management Systems with Time Delays," AIAA-2019
- David O. Sigthorsson, Michael W. Oppenheimer, and David B. Doman, "Aircraft Thermal Endurance Optimization Part 1: Using a Mixed Dual Tank Topology and Robust Temperature Regulation," AIAA-2019
- David B. Doman, "Optimal Cruise Altitude for Aircraft Thermal Management," Journal of Guidance, Control, and Dynamics, Vol. 38, No. 11, Nov. 2015
- David O. Sigthorsson, Michael W. Oppenheimer, and David B. Doman, "Aircraft Thermal Endurance Optimization Part 2: Using a Simple Dual Tank Topology and Robust Temperature Regulation," AIAA-2019
- Michael W. Oppenheimer, David O. Sigthorsson, and David B. Doman, "Extending Aircraft Thermal Endurance by Fuel Pump Sizing," AIAA-2018-0856
- David O. Sigthorsson, Michael W. Oppenheimer, and David B. Doman, "Aircraft Thermal Endurance Enhancement Using A Dual Tank Configuration and Temperature Regulation," AIAA-2018-0612
- David B. Doman, Michael W. Oppenheimer, and William Rone, "A Selective Self-Locking Actuator and Control Allocation Approach for Thermal Load Minimization," AIAA-2015-1756

United States Patent Applications

- Selectively Self Locking Actuator (USPTO Notice of Patent Acceptance Received 18 Sep 2018)
- Thermal Management System and Method of Using Same (Dual Tank Configuration)

Thank You

Dynamic Modeling of Fuel Thermal System: Assumptions

- Equations derived from conservation of mass & energy
- Assumptions
  - Heat exchanges & coolers operate in steady state (no capacitance/incompressible flow)
  - Tanks
    - Instantaneous mixing
    - Uniform instantaneous temperature
    - Work done by pressure at inlet and exit small compared to internal energy changes
    - Vented with inert gas, no phase changes occur
  - Specific heat of fuel constant
- Temperatures interpreted as bulk temps

Enough complexity to capture the salient features while still allowing for analytical solutions to temperature evolution