Approach for Sizing and Turndown Analysis of a Variable Geometry Spacecraft Radiator

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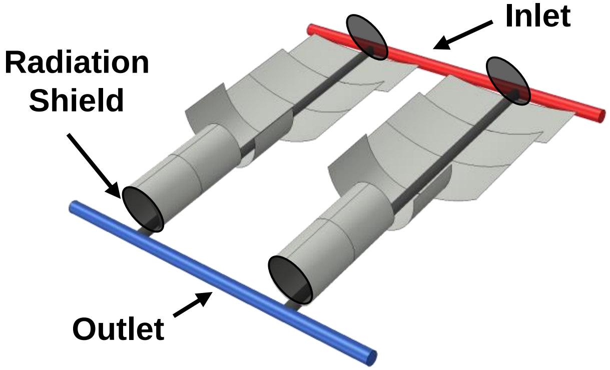
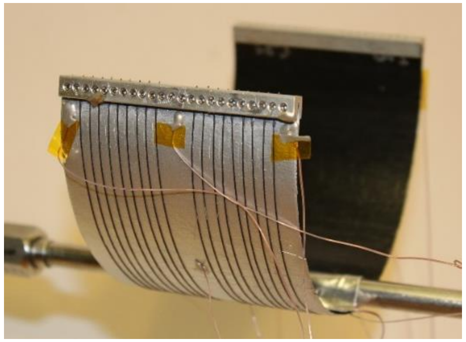
Variable Geometry Radiator

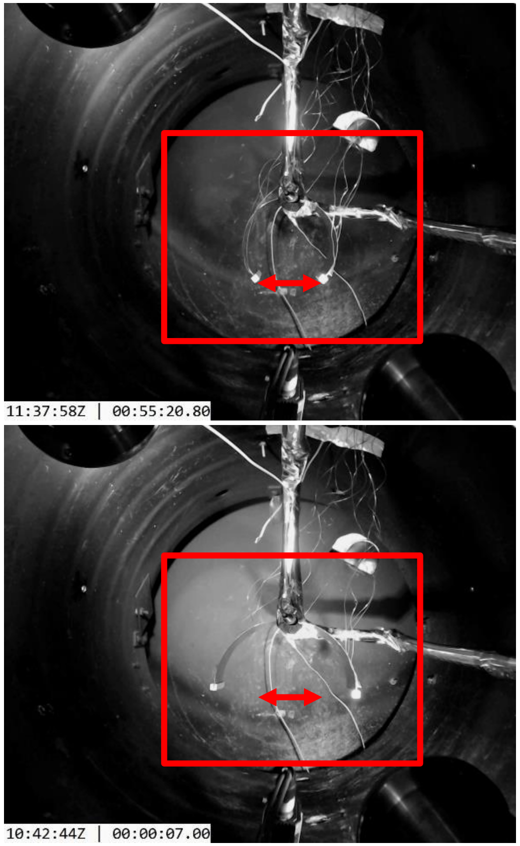
- Aims to **passively increase variable heat rejection** capability by adjusting its view to space.
- Radiator panels **open/close** as a function of temperature using **shape memory alloys (SMAs).**
- JSC funded development targets manned vehicles active thermal control systems (ATCS) to enable single loop architectures.



Operational concept. Many short panels – prevents panel twisting.



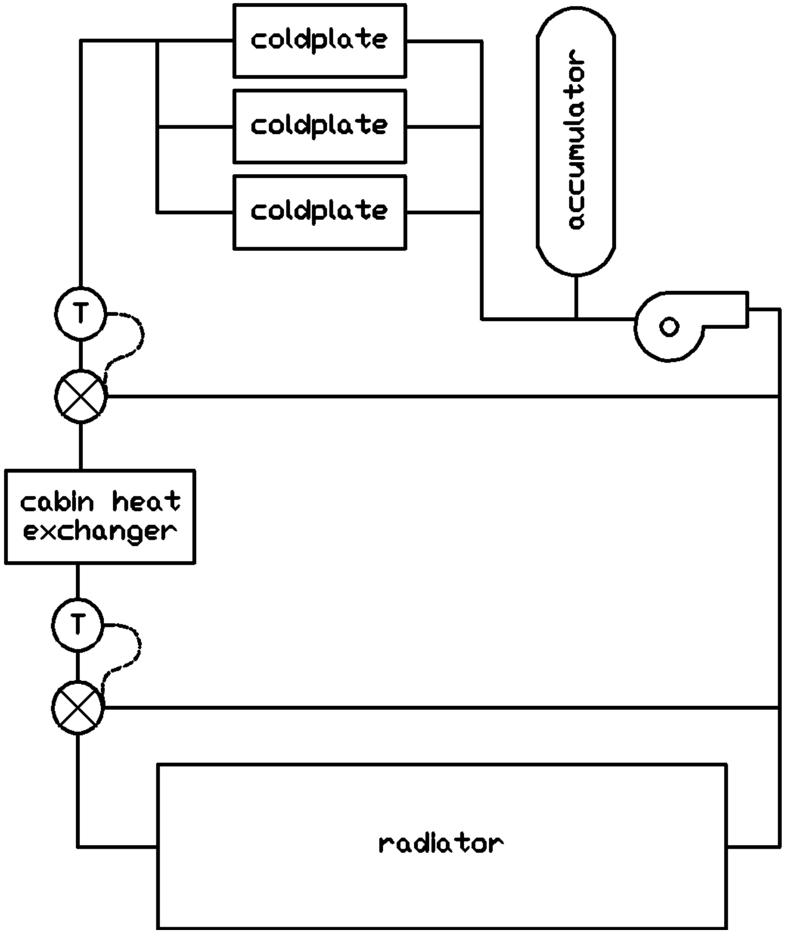
FY16 prototype: SMA wires attached to panel ends.



8/8/16 Thermal vacuum test of composite panel. Panel is naturally open at ambient. Cycled fluid from 80 to -43C.

Purpose of a System Level Model

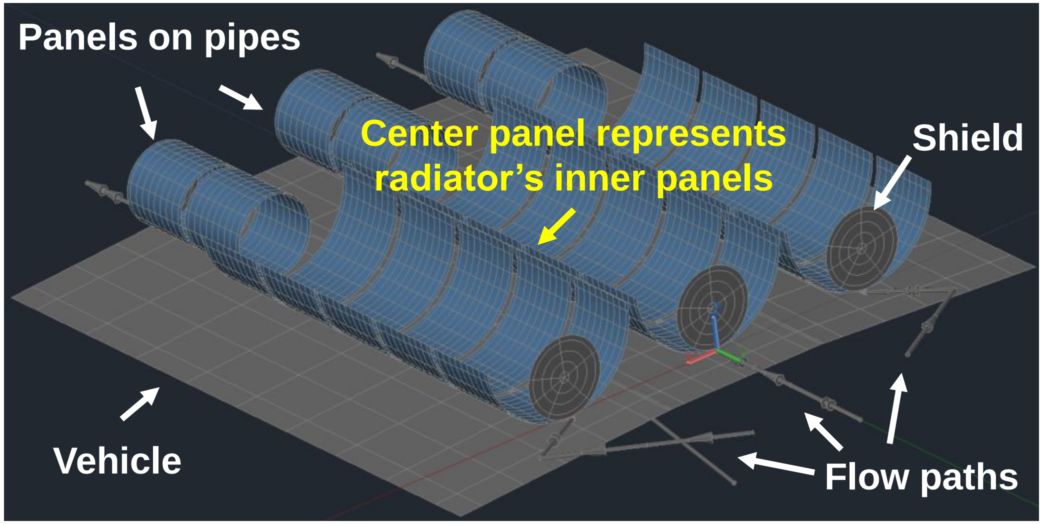
- Evaluate and compare designs by:
  - Sizing radiator (max heat load).
  - Calculating turndown (min load).
  - Both for steady-state operation.
- Model must:
  - Account for radiator's curved panels seeing themselves.
  - Enable easy adjustment of radiator parameters (e.g. optical properties, space between panels, etc.).
  - Enable opening and closing of individual panels.
- Assumed:
  - Body mounted radiators on a cylindrical vehicle.
  - Straight parallel paths with uniform flow distribution.



Single loop ATCS for radiator sizing and turndown calculations.

Modeling Idea

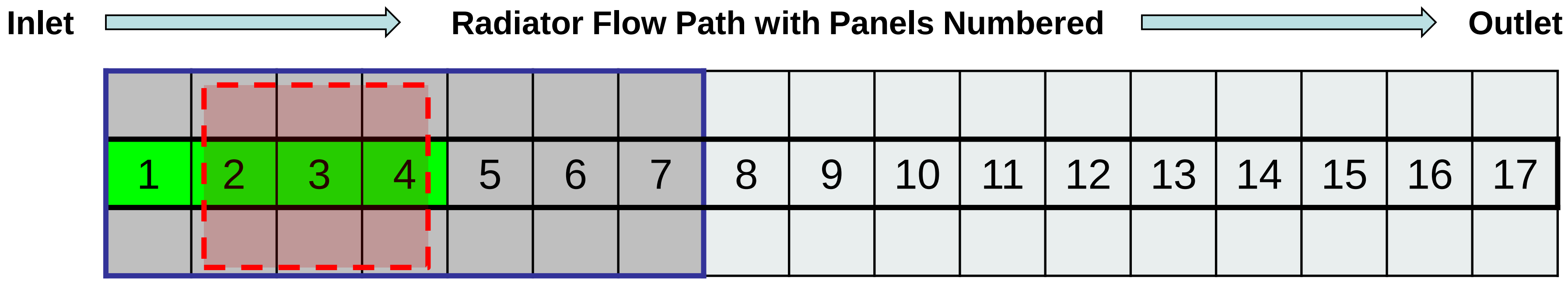
- Build model in Thermal Desktop → capturing panel's 'cavity' effect.
- But a typically sized radiator would require ~1000+ panels.
  - Given prototype panel sizes: 3in long and 6in open diameter.
  - **30m^2 projected area = 2583 panels!**
- **Proposed Approach:** Build a **radiator segment** in Thermal Desktop. Piece together steady-state solutions to **solve for a path**. Repeat for each path to get the solution for **the entire radiator**.



Radiator segment in Thermal Desktop

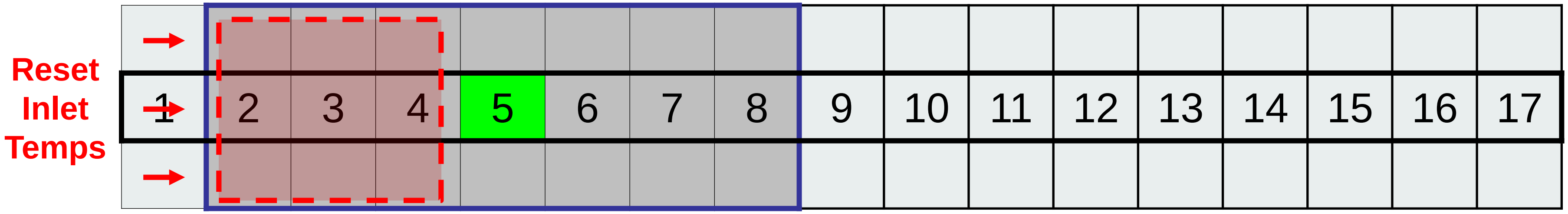
Modeling Idea: Solve for a Path

1. Run steady-state solution for segment at path’s start.
   - For panel’s 1 to 4 record each outlet temperature and heat rejected.



Save panel temperatures

2. ‘Move’ down and run steady-state solution for segment again.
   - Record panel 5’s results.



Reset Inlet Temps

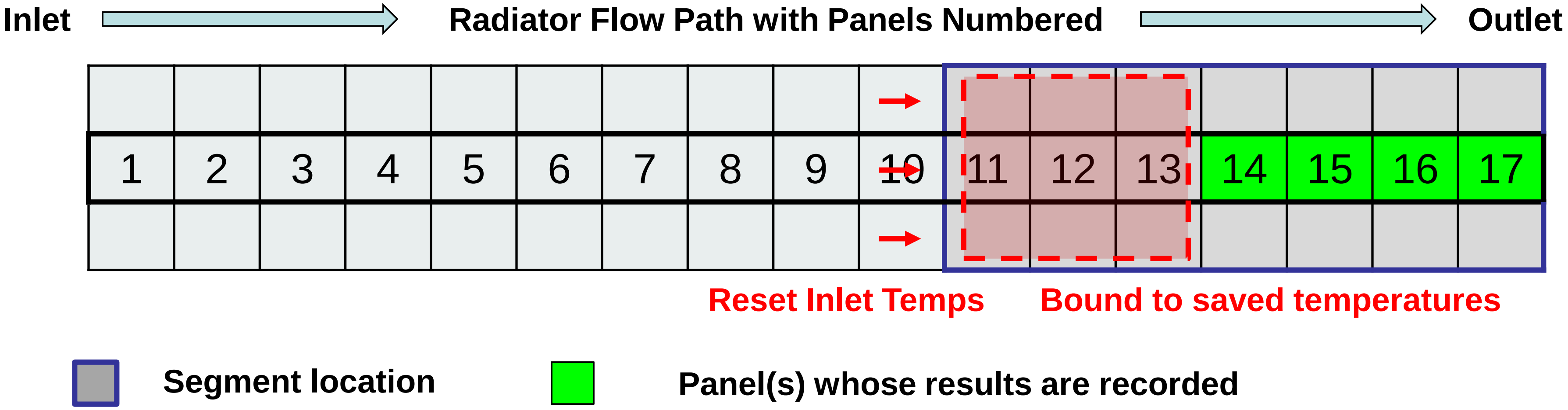
Bound to saved temperatures

▨ **Segment location**

🟩 **Panel(s) whose results are recorded**

Modeling Idea: Solve for a Path

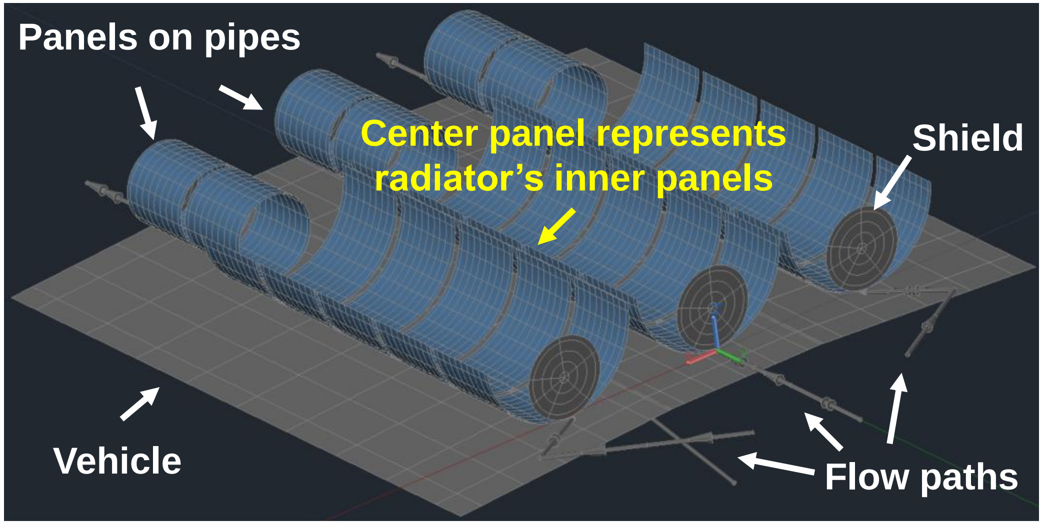
3. Continue to ‘move’ down the radiator’s path.
   - Record results one panel at a time.
4. At path’s end run steady-state solution for segment again.
   - Record each panel’s outlet temperature and heat rejected.



Segment includes: 1) outside paths and 2) multiple panels in a path to provide a representative radiation environment for the panel(s) whose outlet temperature and heat rejection is recorded.

Modeling Idea

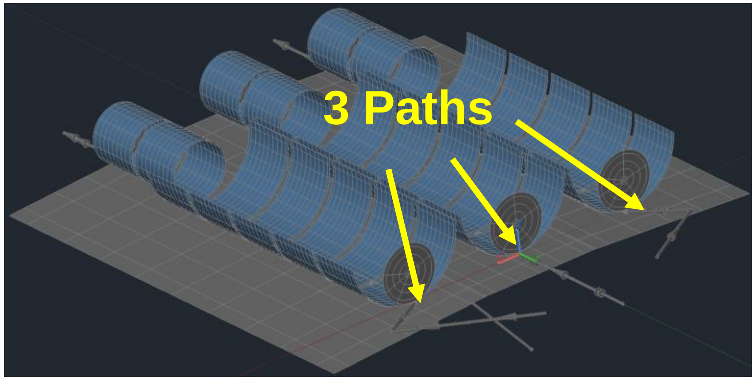
- Use Custom FORTRAN code to essentially:
  - Move segment down the length of a full radiator path.
  - Rotates segment's angle to the sun to move it between paths at different locations around the cylindrical vehicle's circumference.
- Can adjust radiator parameters including:
  - Space between paths, panels along a path (with symbols).
  - Number of panels in a path, number of paths (in code).



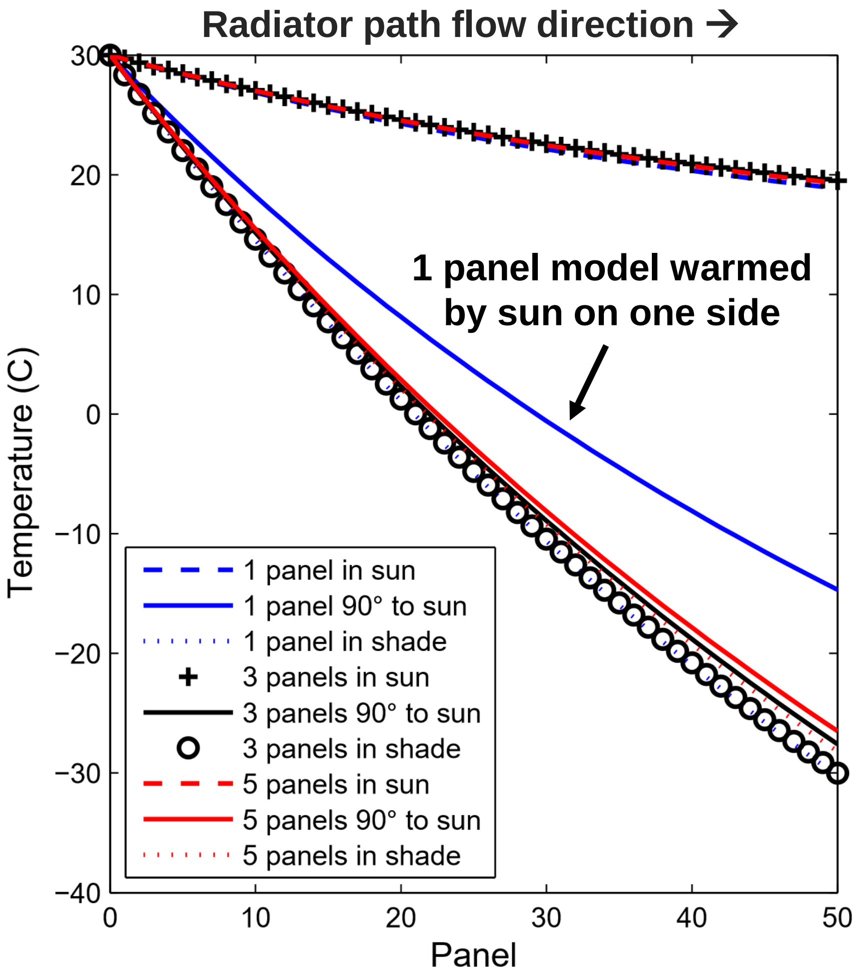
Radiator segment in Thermal Desktop

Choosing Segment Size: Paths

- Compared 3 models varying number of paths in a segment.
  - Each path had one panel.
- MLI or low emissivity convex surface limits heat transferred between paths.
  - Small outlet temp. difference for 3 path (3 panel) and 5 path (5 panel) models.
- **Need >2 paths as adjacent paths block the sun.**



*Results may vary with different configurations.

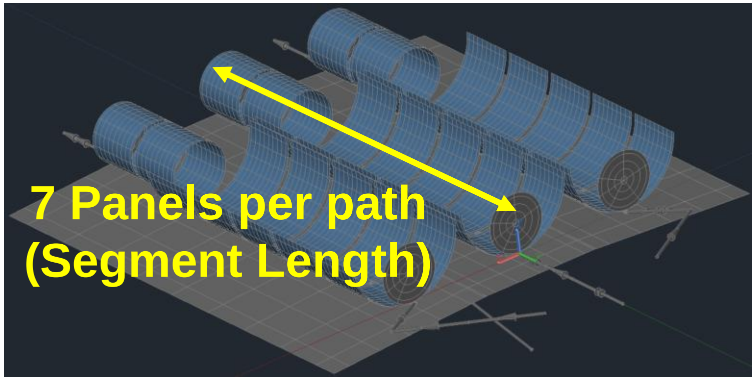


Path outlet temperature comparison.

Case: 0.68lbm/hr per path, radiator shields: ε=0.91/ α=0.29, panel convex: ε=0.83/ α=0.15, panel concave : ε=0.04/ α=0.14.

Choosing Segment Size: Panels per Path

- Compared radiation conducted between center panel and other panels to that between center panel and all components in model (e.g. space, the vehicle).
- Comparison case:
  - Closed panels, facing the sun.
  - 0.25in between panels.
  - Shield only reflect radiation.
- **Need ≥7 panels per path since center panel sees proceeding and following panels.**



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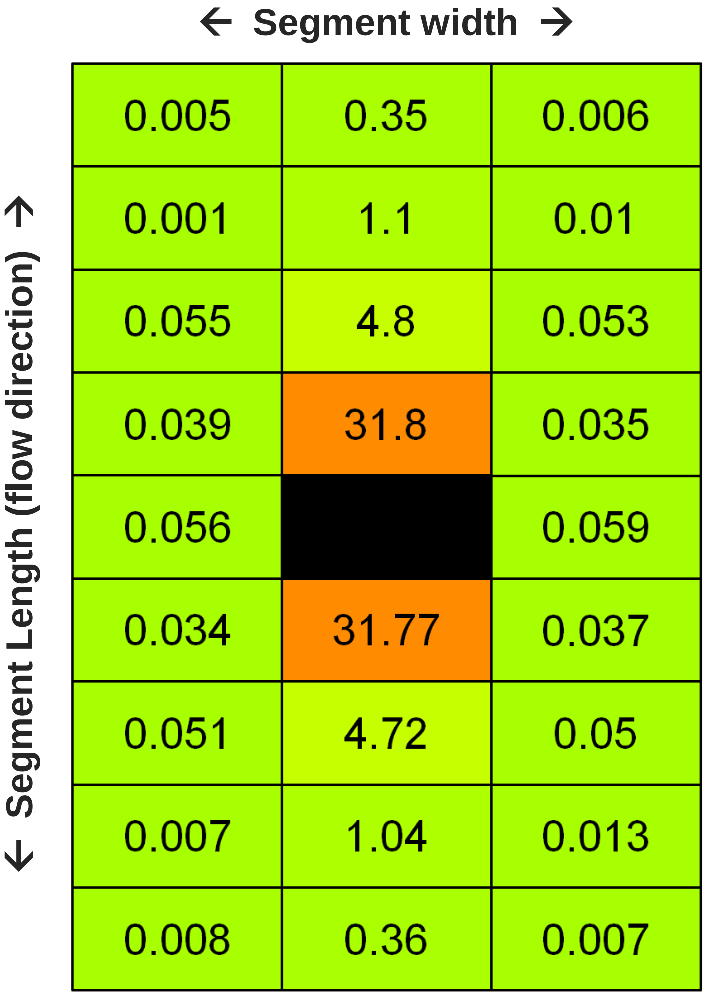


0.005	0.35	0.006
0.001	1.1	0.01
0.055	4.8	0.053
0.039	31.8	0.035
0.056		0.059
0.034	31.77	0.037
0.051	4.72	0.05
0.007	1.04	0.013
0.008	0.36	0.007

Percentages of the total radiation conductance from the center panel to the other panels in the segment.

Modeling Example

- Best to explain how it works with an example.
- Some key parameters:
  - Vehicle Size: Length: 5m / Diameter: 5.5m
  - Vehicle optics: ε=0.03, α=0.2 (3M-425 aluminized tape)
  - Environment: Solar flux: 1414W/m^2 **(No incident infrared radiation)**
  - **Max heat load: 8kW**
  - **Radiator inlet: 30C (full load) to 16C**
  - **Cabin heat exchanger inlet set-point: 4C**
  - **Minimum allowable fluid temperature: -16C** (60/40 water/propylene glycol)
  - Number of fluid paths: 100 evenly distributed around vehicle
  - Space between panels along a path: 0.25in
  - Panel size: Width: 3in / Length: 4.71in / Thickness: 0.0175in
  - Panel concave side optics: ε=0.83, α=0.15 (Optical Solar Reflectors, ideal case)
  - Panel convex side optics: ε=0.04, α=0.14 (aluminized Mylar)
  - Panel thermal conductivity: 238 W/mK
  - **Panel behavior: Open: 4C / Closed: -10C**
- Hottest orientation: Side to sun (one path directly faces the sun).
- Coldest orientation: Tail to sun (all paths see deep space).

Modeling Example: Size Radiator

1. Guess an upper bound path length: 50 panels.
2. Run model in hottest orientation at flow rate needed to reject max heat load at desired temperature drop: 680lbm/hr total.

- FORTRAN subroutines placed in a single logic object in the Object Manager carries out solution process.
- **Vehicle subroutine:**
  - Calls Path subroutine 50 times (by symmetry the other 50 are assumed to be identical).
  - **Changes each path's orientation** around vehicle by adjusting the static orbit's angles.
- **Path subroutine:**
  - Calls Segment subroutine: 44 times.
  - **Sets inlet fluid temperature.**
- **Segment subroutine:**
  - **Calls STEADY** to find steady-state solution.
  - 1st time: records results for 1st four panels in path.
  - 2nd - 43rd times: records results for all middle panels.
  - 44th time: records results for last four panels.
  - Writes to output file for each path.

Start of output file for first path.

```
data_path_001.txt:
Panel # , Tin , Qout, Panel_Angle ,T_base
 0 , 30.0000 , 0.0000 , 180.0000 , 0.0000
 1  ,29.7536  ,0.5696 , 180.0000 , 27.7453
 2  ,29.5720  ,0.5221 , 180.0000 , 28.1561
 3  ,29.4231  ,0.4603 , 180.0000 , 28.1974
 4  ,29.2821  ,0.4331 , 180.0000 , 28.1211
```

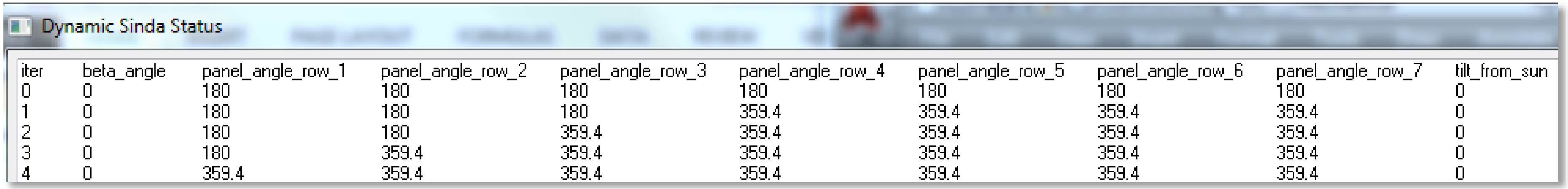
- To string solutions together, path inlets and states of first three panels come from previous segment.

Modeling Example: Size Radiator

- Panels close if previous panel’s root temperature is <-10C.
- Geometry updates by 1st changing registers, and 2nd having SINDA subroutines instruct Dynamic SINDA to communicate the changes to Thermal Desktop.

From path subroutine:

```
call TDSETREG( 'Tilt_from_sun', angle)              ← Sets path location around vehicle
call TDSETREGINT( 'BETA_ANGLE', BETA_ANGLE)         ← Sets orientation of vehicle (e.g. tail or side to sun).
call TDSETREG( 'panel_angle_row_1', P_ANG)          ← Sets first panels in each path as open or closed.
….
call TDUPDATE                                       ← Adjusts model’s geometry.
call TDCASE                                         ← Instigates new radiation calculations.
```

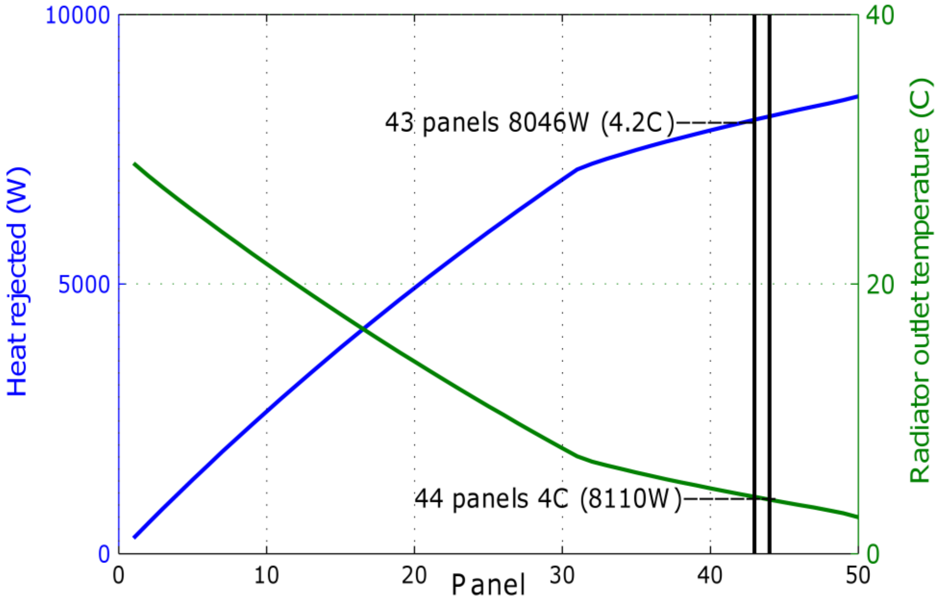


```
iter  beta_angle  panel_angle_row_1  panel_angle_row_2  panel_angle_row_3  panel_angle_row_4  panel_angle_row_5  panel_angle_row_6  panel_angle_row_7  tilt_from_sun
0     0           180                180                180                180                180                180                180                0
1     0           180                180                180                359.4              359.4              359.4              359.4              0
2     0           180                180                359.4              359.4              359.4              359.4              359.4              0
3     0           180                359.4              359.4              359.4              359.4              359.4              359.4              0
4     0           359.4              359.4              359.4              359.4              359.4              359.4              359.4              0
```

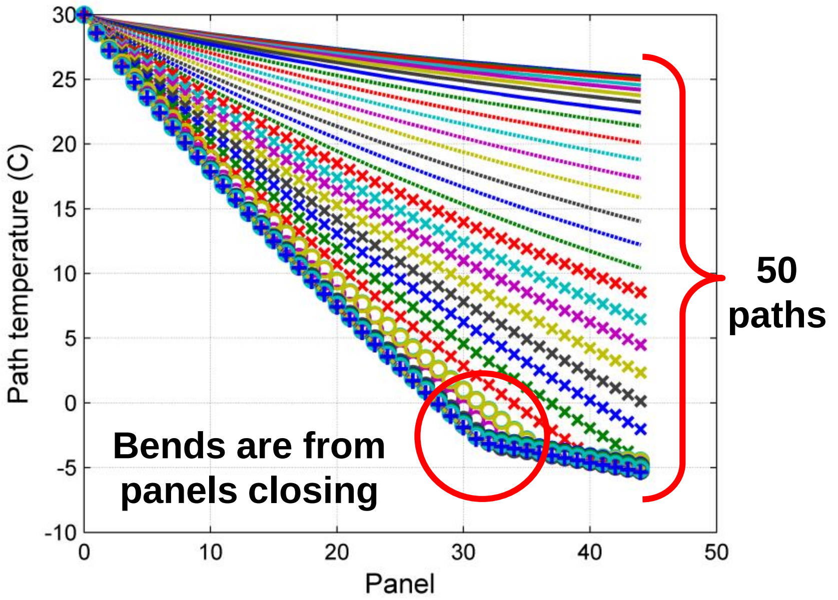
Dynamic SINDA status window shows updates. In iter 0 the path’s 4th panel was <-10C.
As a result, in iter 1 the segment, now modeling panel’s 2 to 5, shows subsequent panels closing.

Modeling Example: Size Radiator

3. Read output files into MATLAB.
4. Determine, for radiators 1-50 panels long, total heat rejected and outlet temps.
5. Search results to find number of panels needed.
   - **44 panels per path (4400 total)**
6. Confirm minimum path temperature is >-16C.
7. Verify pressure drop in coldest path is not too high.



Model results marking panel number that meets requirements.



50 paths

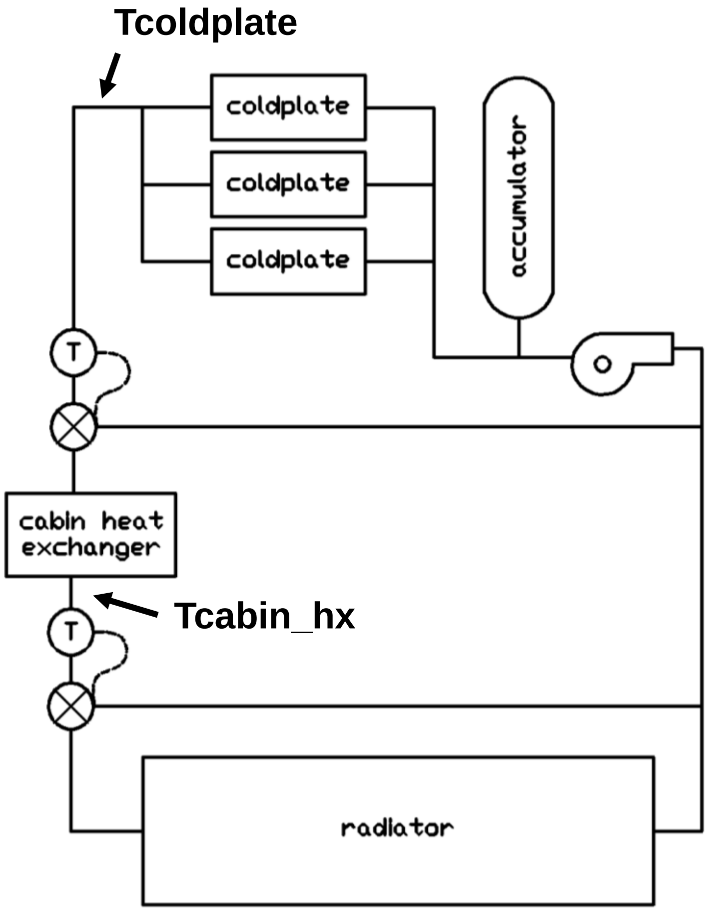
Bends are from panels closing

Fluid temperature along each path.

Modeling Example: Turndown

1. Run cases in coldest orientation varying flow rates and inlet temperatures.
   - Only one path needs to be solved since all paths have identical inlets and environments.
2. Read output files into MATLAB.
3. Find total heat rejected and Tcabin_hx.

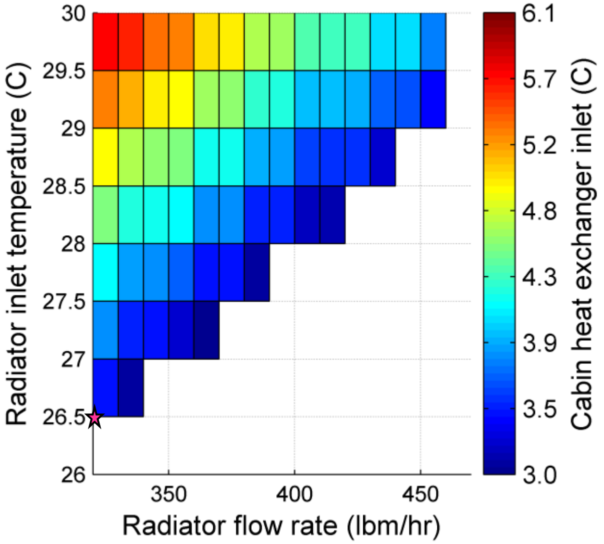
- Radiator bypass maintains Tcabin_hx.
- Internal bypass maintains Tcoldplate.
- Get Tcabin_hx assuming linear relation between internal bypass flow and the total heat load.
  - At full load 80% of total flow is diverted to the radiator and its bypass.
  - At ¼ load 40% of total flow is diverted to the radiator and its bypass.
  - [Relationship based on paper ref 10.]



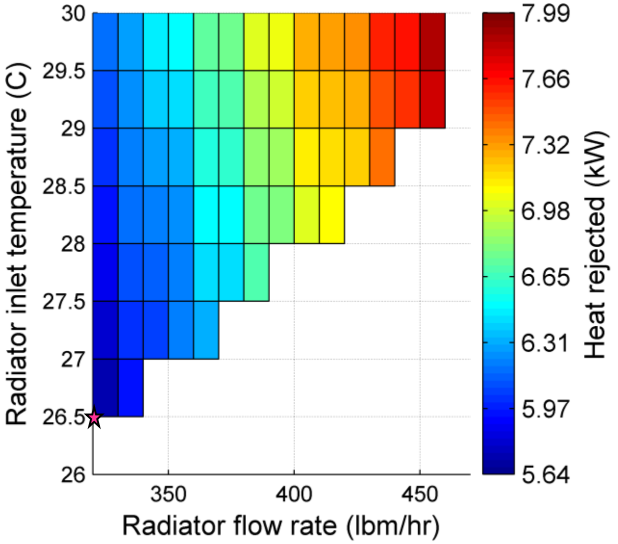
ATCS used for identifying the minimum operational heat load at the coldest orientation.

Modeling Example: Turndown

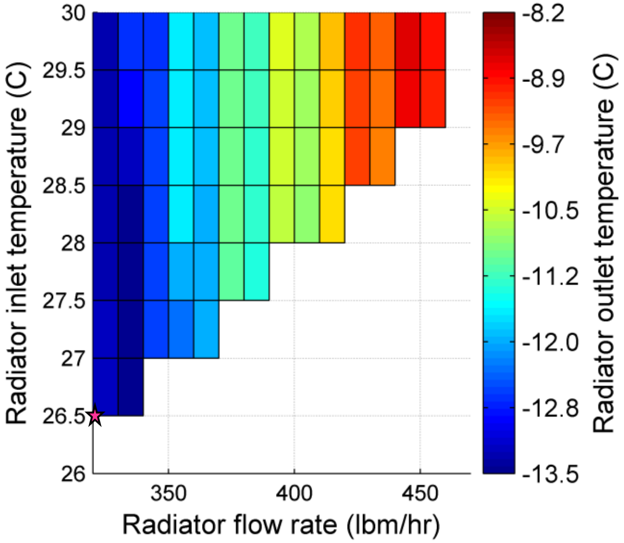
4. Interpolate and plot results, eliminating cases outside acceptable range.
   - Minimum operating condition for 3.4C cabin heat exchanger inlet set point:
     - 26.5C radiator inlet and -13.3C outlet
     - 5.71kW rejected
     - 320lbm/hr through the radiator and 231lbm/hr through the radiator bypass
     - 35% of the panels are open



Cabin heat exchanger inlet (C).



Radiator heat rejection (W).



Radiator outlet temperature (C).

Note: Performance varies for different radiator configurations.

Modeling Checking

- Verified model outputs were reasonable.
- Radiator sizes predicted with model agreed with those predicted with simple hand calculations.
  - Found projected area, A_p, needed with energy balance.
  - Found fin efficiencies, η, and sink temperatures using model.

Type	$T_{sink,shade}$ (K)	$T_{fluid,avg}$ (K)	Q_{ideal} (W)	Q_{actual} (W)	η	$T_{sink,avg}$ (K)	A_p (m^2)	N_{panels} $(hand)$	N_{panels} $(model)$
Flat	0.0	289.9	123.5	104.3	0.844	195.0	35.9	30.8	31
Curved	38.0	289.7	123.2	103.3	0.838	224.0	44.4	38.2	37

Conclusions

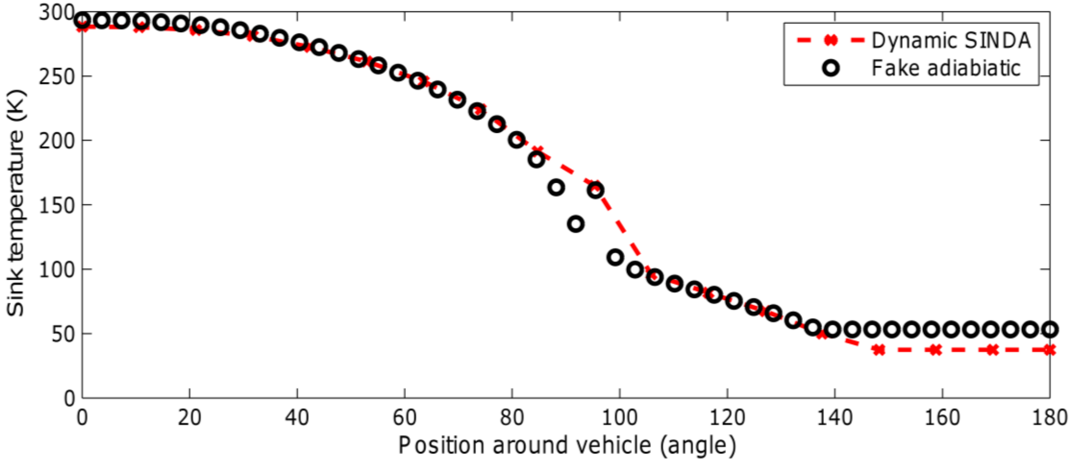
- This approach is useful for trading different radiator configurations with steady-state sizing and turndown predictions.
- Model is not intended for transient analysis.
- Incident infrared radiation is not implemented.
- Parameters can be adjusted and additional details can added to reflect different radiator designs.
- Model's accuracy could be improved by including the ability to partially open and close panels.

BACKUP

Finding Sink Temperature

- Method 1) Run the model with very low flow rate and all panels open or closed.
  - Fluid will approach the sink temperature (i.e. the steady-state temperature achieved with no applied heat load).
- Method 2) Use built in SINDA subroutine TSINK1 to calculate sink temperature for each node in segment's center panel. Then find the panel's average sink temperature. Repeat for different locations around vehicle using Dynamic SINDA. ← Fluid submodel must be disabled for this to work.
  - $T_{sink,avg} = \sqrt[4]{\frac{\sum_{i=1}^{number\ of\ nodes} T_{sink,i}^4}{number\ of\ nodes}}$

Results agree. Second method is much quicker.



Sink temperatures predicted for side to the sun orientation.

Finding Fin efficiencies

- The actual heat rejection per panel, $Q_{p,actual}$, and average fluid temperature, $T_{f\ avg\ path}$, was predicted by the model for a string of panels in a path facing deep space.
- $Q_{ideal} = \varepsilon\ \sigma\ A_p\ \left(T_{f\ avg\ path}^4 - T_{sink\ avg}^4\right)$
- $\eta = \frac{Q_{actual}}{Q_{ideal}} = \frac{\sum_{p=1}^{ptot} Q_{p,actual}}{Q_{ideal}}$