High-Efficiency Polar Heavy Traverses

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Jason Weale & Jim Lever ERDC-CRREL

US Army Corps of Engineers

Engineer Research and Development Center

Key Points

Thank you NSF, CRREL, RPSC-LM,CPS(PFS)…
Arctic-Antarctic Collaboration nets Rapid Design Cycles
Plastic Sleds Make a [Huge] Difference
Bladders Addressed the Fuel Challenge
Cargo Sleds have Evolved
Economic Analyses Justify Investments
If You Build it…

Goal: Develop & Apply Technology to Address the Polar Logistics Paradigm

Consider this a Case Study
- Think “Moneyball” for Polar Logistics & Operations
- Method is applicable to all logistics/science challenges

Haul Heavy Cargo Over Unprepared Snow
- Resupply stations, install/remove camps
- Enable science along existing routes
- Enable science where airlift cannot currently operate

Efficiency/Cost Justification vs. Aircraft Status Quo
- Save money, hedge cost increases
- Lower fuel consumption & emissions
- Carry oversize/overweight cargo
- Free up LC-130s & other air support for remote science

Efficiency = Payback

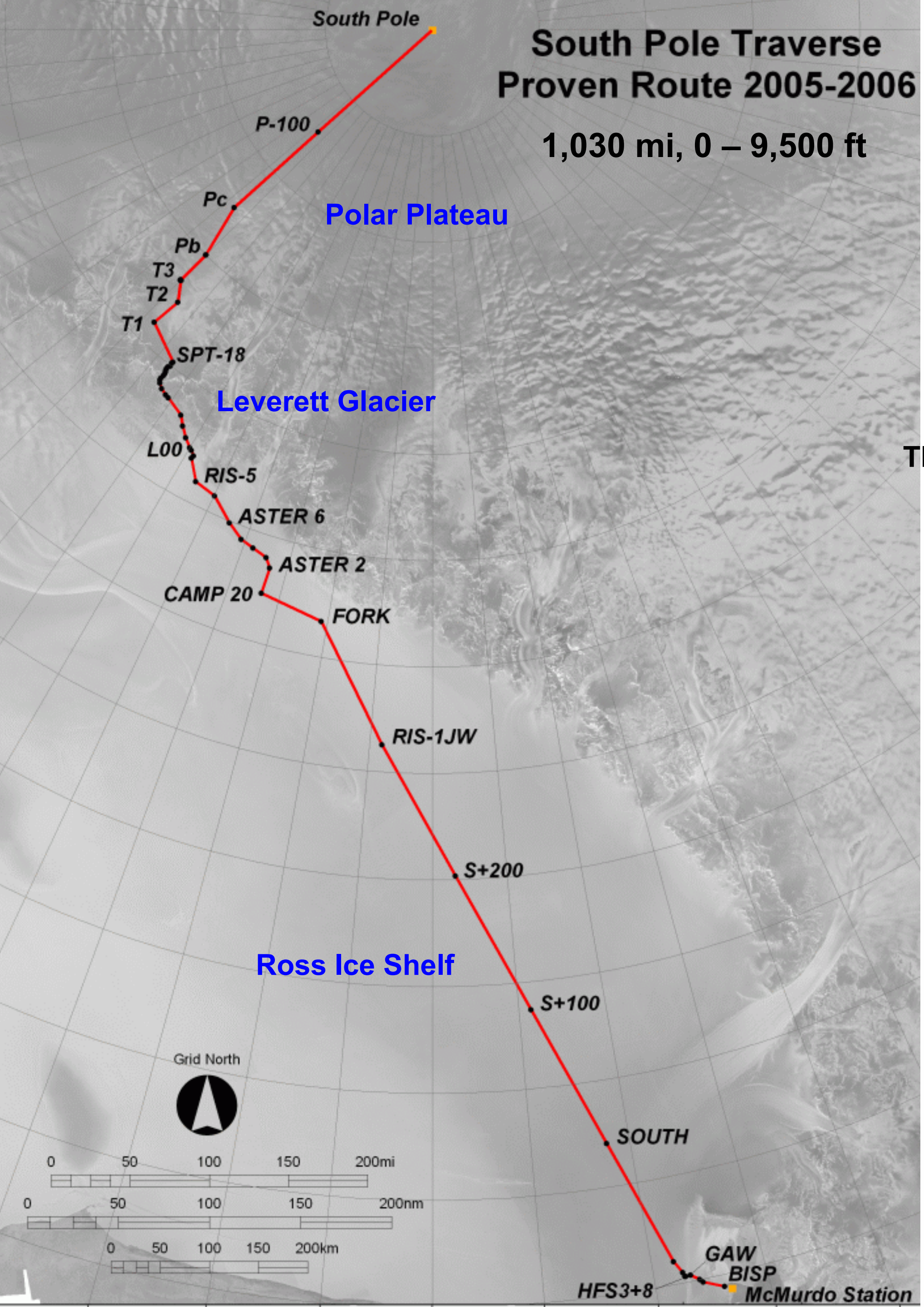
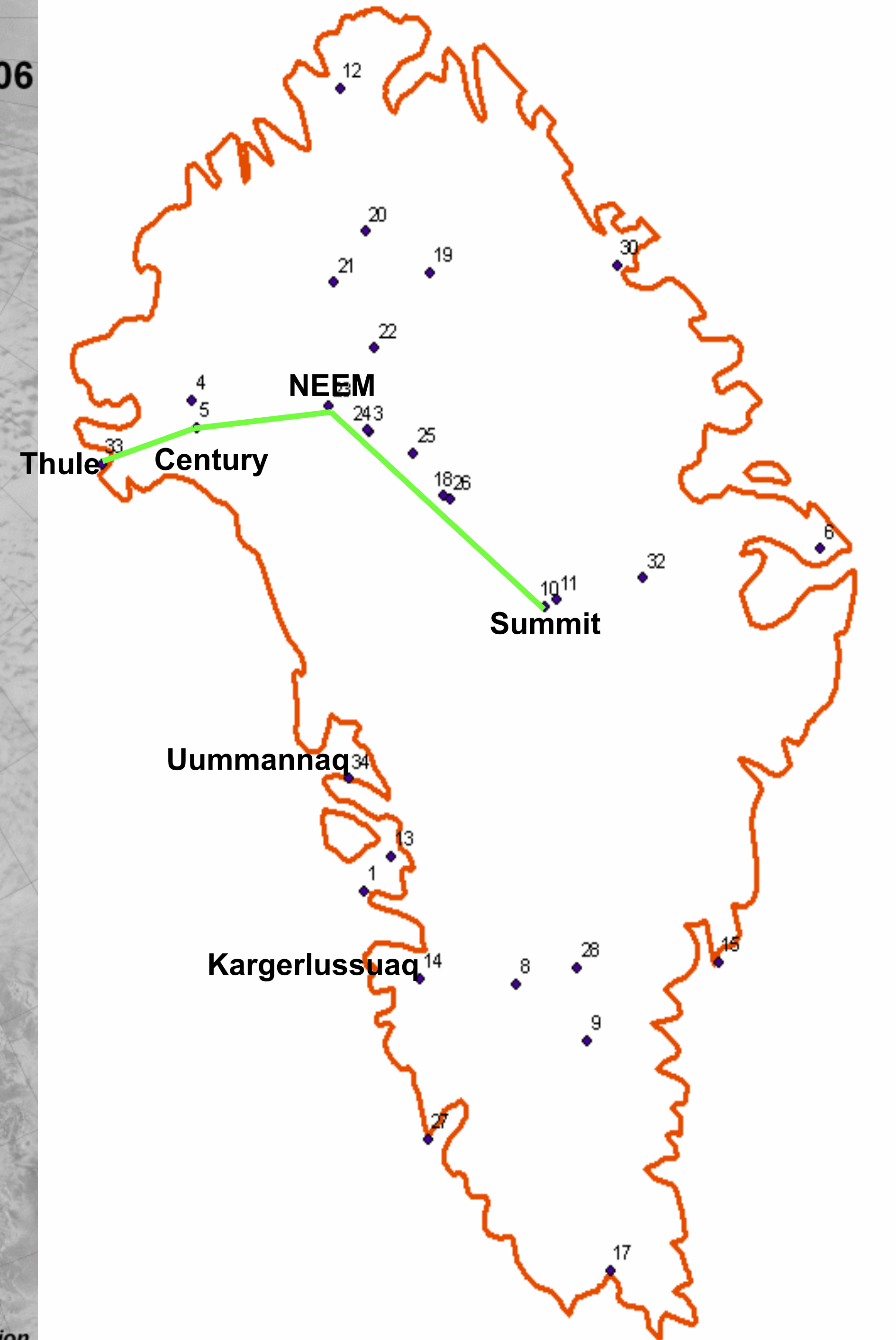
Maximize return on investment

- High payload per tractor
- Minimum transit time
- High reliability
- Low capital & operating costs

Limited tractor options

- Engine power, track width

Focus on sled improvements


South Pole Traverse
Proven Route 2005-2006
1,030 mi, 0 – 9,500 ft
South Pole
P-100
Pc
Polar Plateau
Pb
T3
T2
T1
SPT-18
Leverett Glacier
L00
RIS-5
ASTER 6
ASTER 2
CAMP 20
FORK
RIS-1JW
S+200
Ross Ice Shelf
S+100
SOUTH
GAW
BISP
HFS3+8
McMurdo Station
Grid North
0 50 100 150 200mi
0 50 100 150 200nm
0 50 100 150 200km

NEEM
Thule
Century
Summit
Uummannaq
Kargerlussuaq

Fuel Sled Innovations

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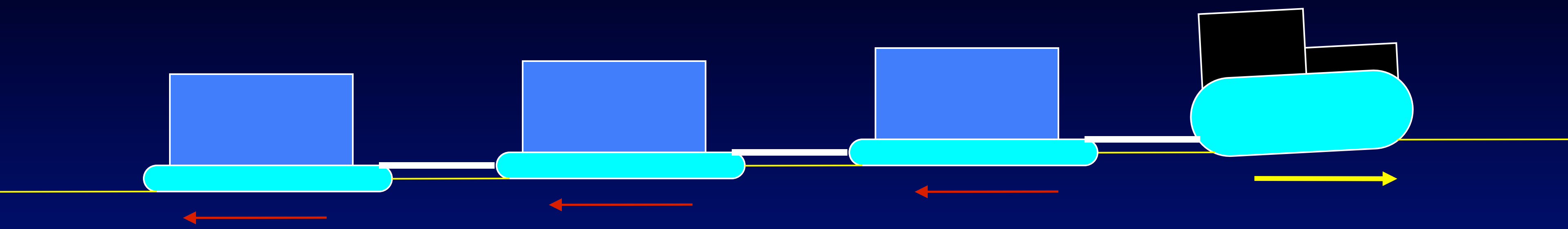
Sled Towing Resistance



Resistance = friction + snow compaction + ~~plowing~~

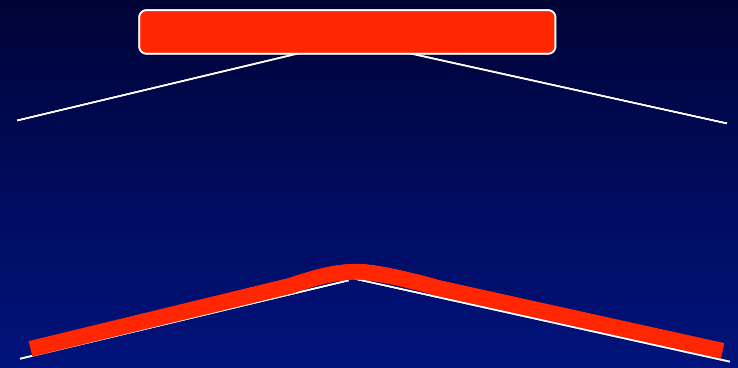
$$R = (W_p + W_t) \times (\mu + 2p_0/kL)$$

$= z/L$

- minimize tare weight, W_t
- minimize sliding friction, μ
- minimize ground pressure, p_0
- seek uniform ground pressure
- maximize sled length, L

Payload Efficiency = payload weight/towing force

Steel Ski vs. Flexible Sled



- **Steel Ski**
  - **High local pressure (crush snow)**
  - **Slamming motion over peaks**
  - **Stiff structure increases weight & cost**
  - **Short length = higher friction**
  - **High conductivity carries away frictional heat**
  - ***Durable***

Lightweight, Flexible Fuel Sleds

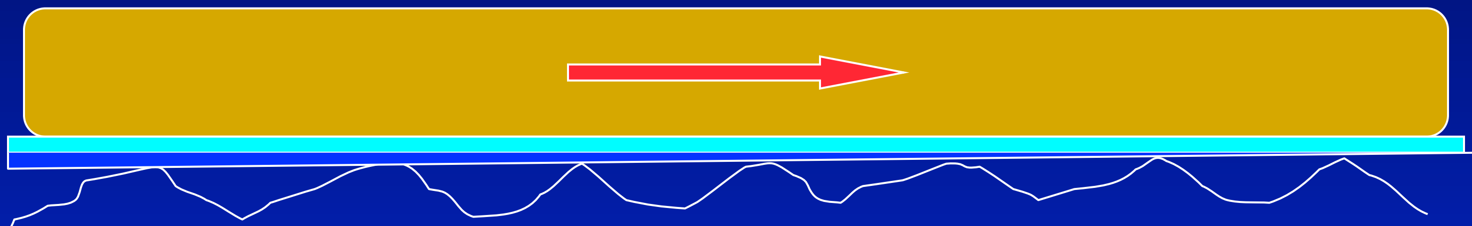
Test First! Bladder Durability (-29 C)

Field Performance Monitoring

- Sled resistance
- Tractor drawbar pull
- Tractor speed, location & altitude
- Sled-snow interface temp.
- Fuel & air temperatures
- Solar irradiance
- Snow strength & rut depths

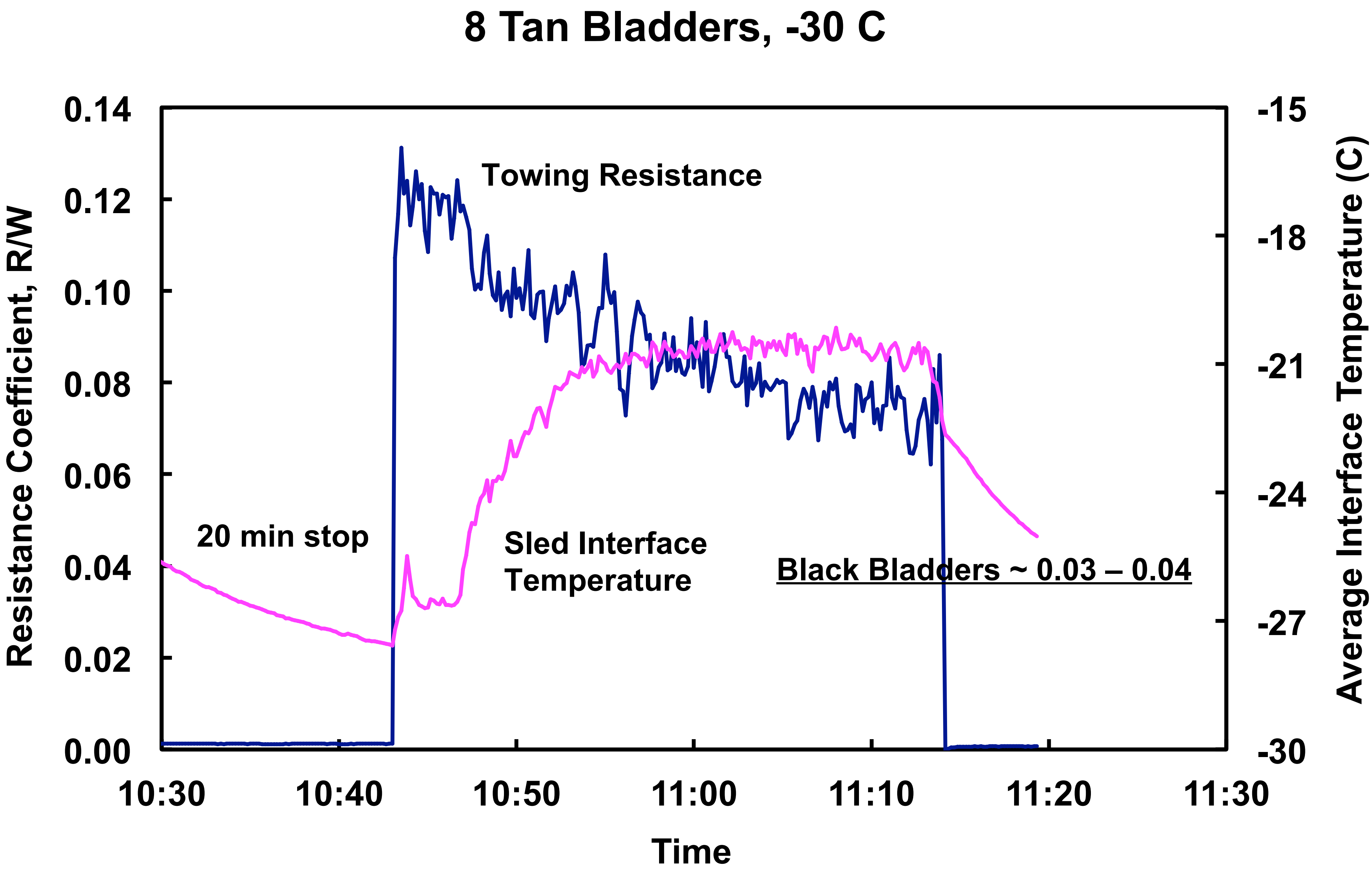
Sled-Snow Friction

- High friction ($\mu \sim 0.3$) when sleds are cold
- Frictional heating melts snow contact points
- Lubricating water layer reduces friction



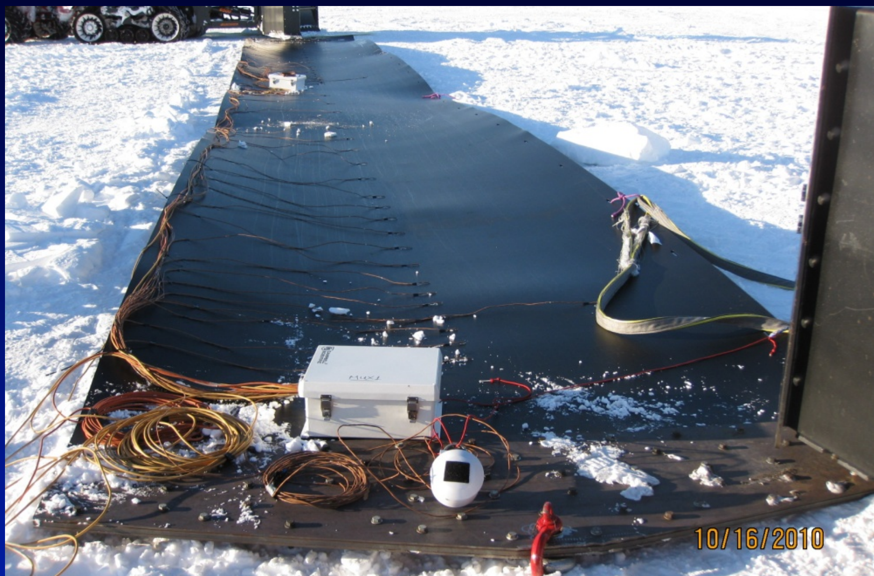
- Sleds warm up over 10-30 min, resistance drops
- Design to maximize sled temperature
- Two bladders inline, black bladders

Sled Warm-Up



8 Tan Bladders, -30 C
Towing Resistance
20 min stop
Sled Interface Temperature
Black Bladders ~ 0.03 – 0.04
Resistance Coefficient, R/W
Average Interface Temperature (C)
Time
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-15
-18
-21
-24
-27
-30
10:30
10:40
10:50
11:00
11:10
11:20
11:30

Black vs. Tan Bladders



- Instrument group of 8 black & 8 tan bladders
- Sled-snow interface, fuel & air temps, solar irradiance
- Load cell for each group

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Efficiency Comparison (3,000-gal capacity)

	Steel Tank	Tan Bladders	Black Bladders
Tare Weight (lb)	12,400	1,200	
Cost	$100,000	$15,000	
Towed Per Tractor	4	8	12 - 16
S.Pole Delivery per Tractor	2	6	10 - 14

3x 2x

- **SPoT2 towed 12 & 16 black bladders this year!**

What About Cargo Sleds?

- Very poor towing performance
  - 25,000 lb tare for 20,000 lb cargo
  - high sinkage & friction
- Expensive: ~ $90 – $100k per sled

Air-Pillow Suspension: Rapid Evolution

Tube-in Pouch Suspension

Advantages

- Existing fabric technology
- Pouch is structural & keeps out snow
- Easy to swap tubes
- 1/5 tare weight,1/4 cost
- 3 x payload efficiency

Pine Island Glacier (PIG) traverse

- ~ 1,700 mi x 4 sleds
- Great ride over sastrugi
- No abrasion problems
- No leaks

GrIT12 (currently en-route)

- Five 16' x 20' decks
- Outsized & heavy cargo
- No leaks

Program Challenges

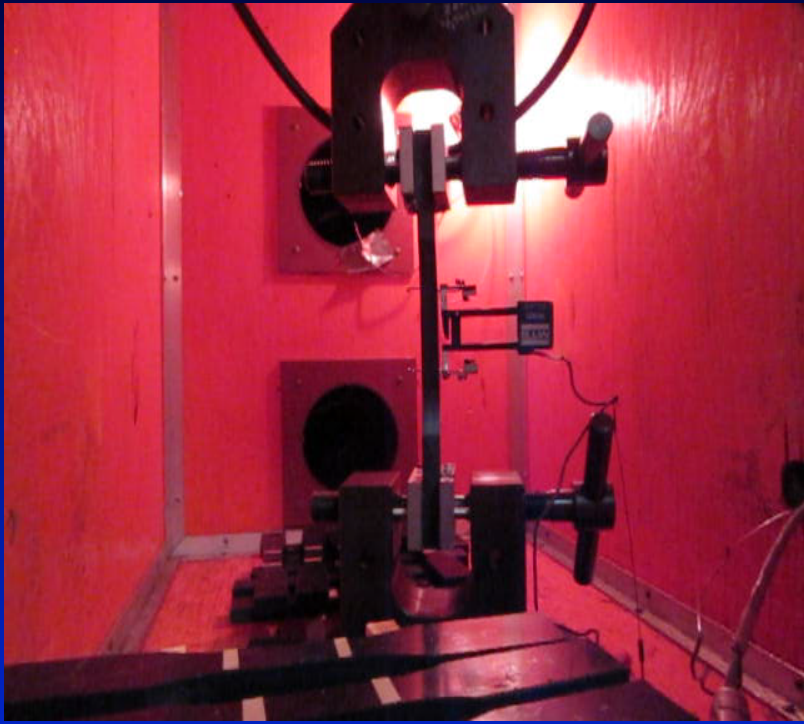
- UHMW-PE to HMW-PE to HMW (improved mix)
- Bladder Sleds Weeping
- Proof of Economic Benefits

HMW *Sled Failures & Weeping Bladders*

- Need to evolve durability through development of test, evaluation and development of design requirements

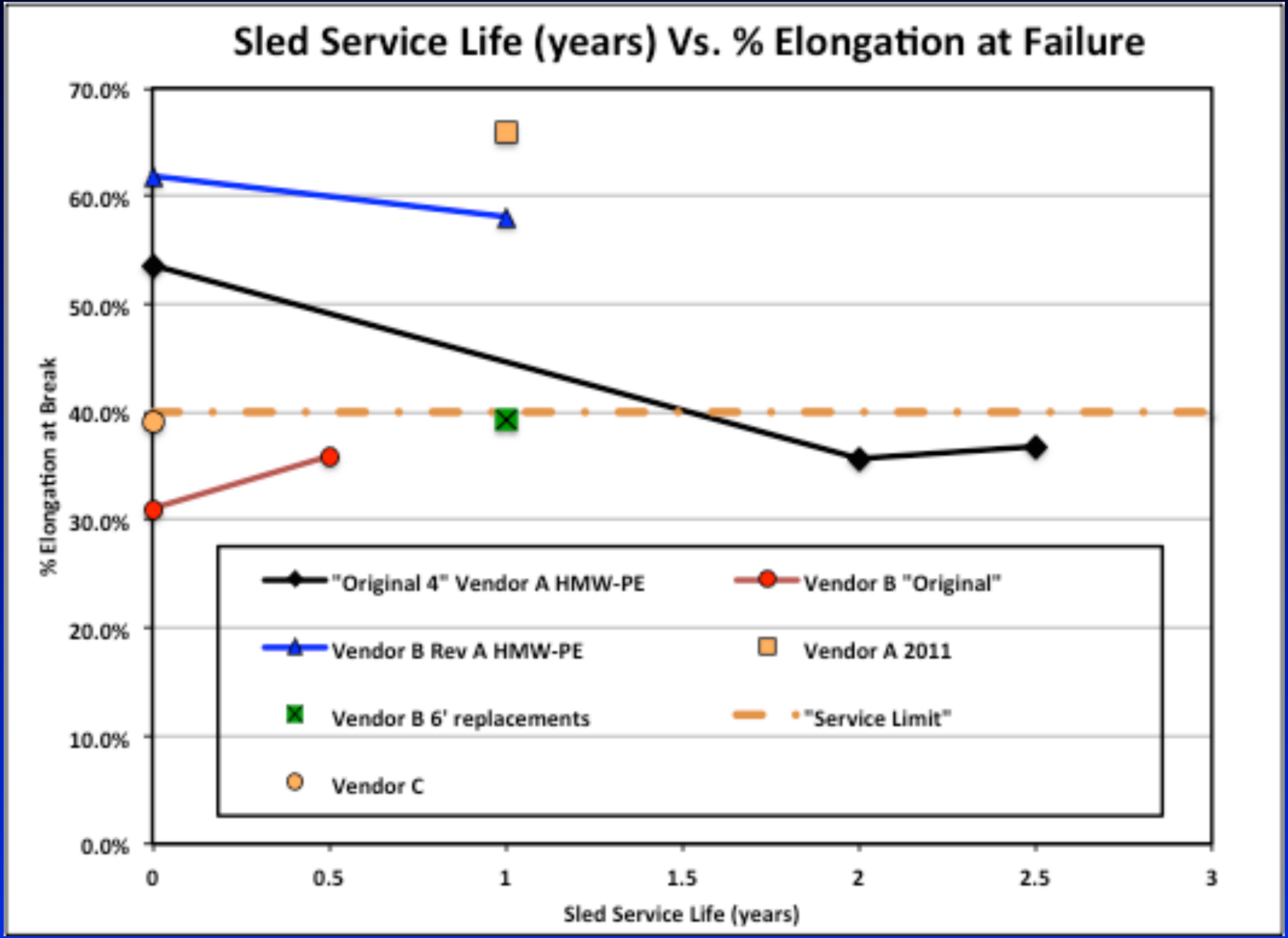
- Initiated a testing program in winter/spring 2011
- Continuing in 2012

Tensile Test Method: HMW-PE "Mixes"



- Selected ASTM D-638 "Standard Test Method for Tensile Properties of Plastic" as an evaluation/comparison method
- In 2011: compared behavior of new and field-service plastic samples at varying temperatures and strain rates
- Results were presented in reports in May 2011
- Determined that -40C and a 20in/min strain rate (MTS crosshead speed) were representative of sled field conditions traveling over sastrugi on the polar plateau.
- Currently testing "modified mixes"

Defining Plastic Behavior…Predictable?



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Leading Issues/Lessons Learned

1. Why a reduction in elongation over time?
    a) UV exposure & fuel contact
    b) Service conditions/physical damage as primary cause
    c) Combination of decreased temp. and tight radius bends (sastrugi)

2. Are we at the limit of QC/QA for COTS products?
    a) Varying results based on identical spec. sheets
    b) Small % changes in elongation at break cause durability and logistics problems in the field

3. One potential key to the breakdown
    a) HMW plastics are polycrystalline materials with complex micro-structures
    b) Are we witnessing a crystallinity change due to our service conditions?
    c) The complex crystalline regions may be unfolding over time…this is one explanation that may describe the ductility we observe – theory needs further exploration

Moving Forward

1. Tensile test method is best tool yet for defining HMW-PE characteristics

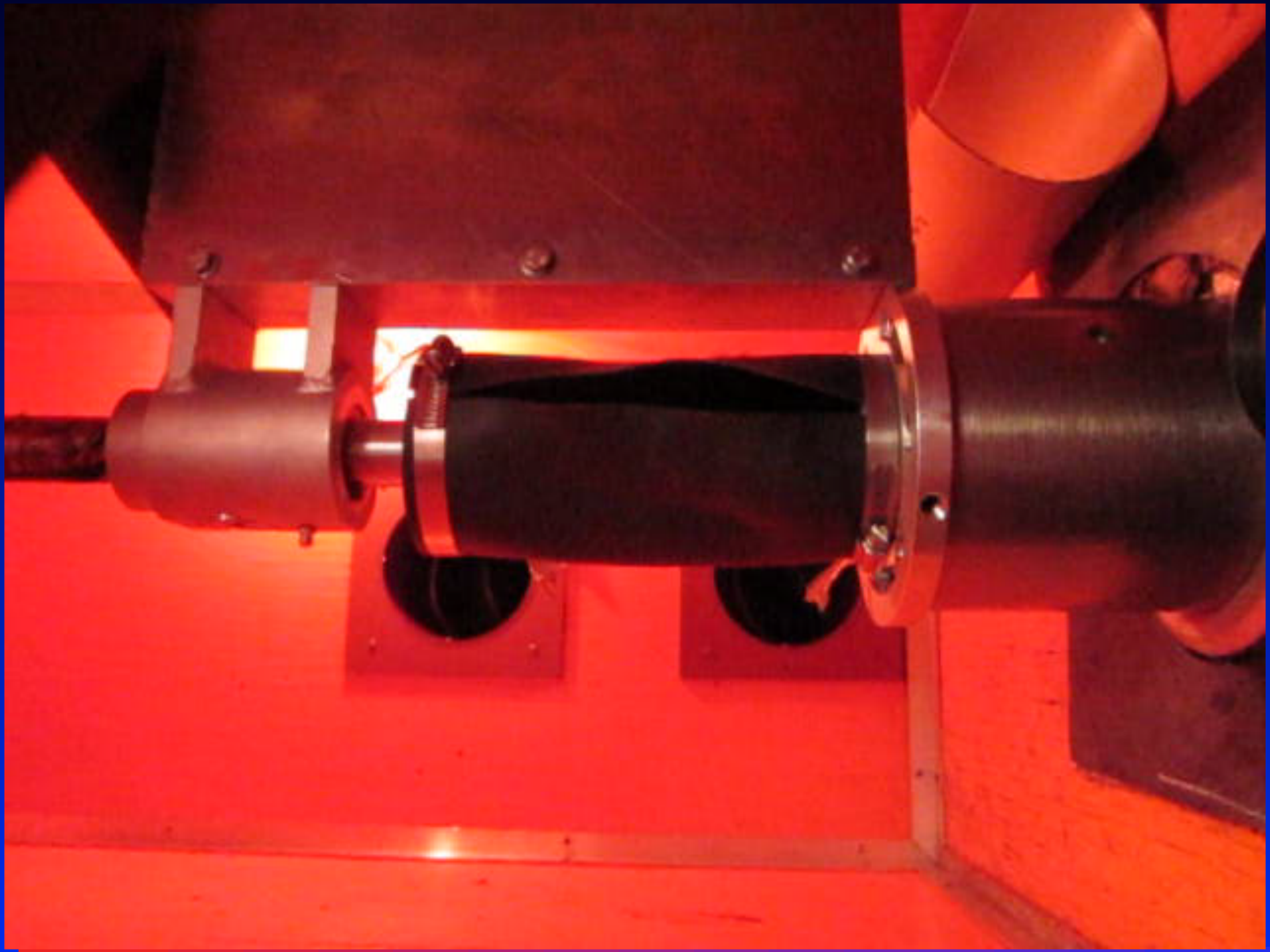
2. Need to look into crystallinity of these plastics (Trovillion)

3. Performance specifications are critical
   a) -40C service temp & 20 in/min crosshead speed
   b) Critical limit of elongation at failure : 40%= remove sleds from inventory
   c) Set target specification at minimum 60% elongation at failure for new materials
   d) Target 4-5 field season service life as interim solution for HMW base sled material

4. Vendors are willing to work with us on custom mix designs
   a) Adding lower density PE to HMW improves performance
   b) Vendor A and Vendor B have both had success
   c) Best to work from HMW and add increasing % of lower density PE

5. "Next Generation" sliding surfaces – composite fabrics, etc.

Bladder Material Tests



Lesson Learned…

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Economic Payback

- Analyze 1st three operational seasons
  - 2008 - 2011
  - Average delivery 768,000 lb
  - > 90% was fuel in high-efficiency bladder sleds
  - Average 30.0 LC130 flights offset/season (25,600 lb/flight)
  - SPoT costs well known
  - LC130 costs harder to compile & apportion to NPX airlift

- Structure analysis to consider other destinations & additional efficiency gains
  - AGAP recovery
  - Black bladders
  - Autonomous tractors

South Pole Airlift Costs

- 2008-11 averaged 215 S.Pole flights/season
- Apportion LC130 costs based on fraction of total on-continent flying hours (56%)
- Components:
  - capital cost of 4 NSF-owned planes (2% p.a., 50 years)
  - 109th AW contract
  - Christchurch depot-level maintenance
  - fuel @ $4.70/gal in McMurdo
  - overhaul/upgrade/repair costs
    - 20 – 30 yr old planes
    - Apply only to NSF-owned planes
    - Placeholder until research historical costs
- Should (but didn't) apportion airfield/skiway costs
  - would need to research

Cross-Checks

- Arctic SAAM rate
  - $8,000/hr
  - Add 0.75 x Greenland hours for positioning
  - Includes fuel
  - Net per on-island = $14,000/hr (probably much higher)
  - Equivalent South Pole airlift = $17,900/hr
    - includes fuel
    - no capital, maintenance or overhaul costs
    - 109th contract includes positioning
- Cost/lb
  - AMC Baltimore-Thule = $7.10/lb
  - S.Pole airlift = $6.10/lb

Net Benefits

Annual economic benefit

- SPoT costs = $2.75M/yr (capital + operating)
- 30.0 flights/yr offset @ $157k/flight
- Airlift costs = $4.72M/yr (capital + operating)

- Net benefit = $2.0M/yr
- Payback capital in 2.3 yrs (43% return)
- Reduce airlift costs or use LC130s for higher-value missions

Emissions Benefits

- Follow Comprehensive Environmental Evaluation (NSF 2004)
- SPoT consumes 42% of LC130 fuel per lb delivered
- CO_2 reduction scales with fuel use

		Normalized Emissions (lb/1000-lb fuel consumption)					
Delivery Mode	**Fuel Consumed (1,000-lb)**	**Sulfur Oxides**	**Nitrogen Oxides**	**Carbon Monoxide**	**Exhaust Hydro-carbons**	**Particulates**	**Average Emission Ratio**
SPoT (CEE)	1387	0.079	0.043	0.016	0.002	0.003	
LC130 (CEE)	2220	1.35	10.66	7.16	3.19	2.93	
SPoT/LC130 emission ratio per unit fuel use (CEE)		5.9%	0.40%	0.22%	0.07%	0.12%	1.3%
SPoT/LC130 average fuel use 2008-11	0.422						
SPoT/LC130 emission ratio per unit payload delivered to South Pole 2008-11		2.5%	0.17%	0.09%	0.03%	0.05%	0.56%

Economic Conclusions (to date)

Annual South Pole deliveries 2008 - 2011

- 768,000 lb, mostly fuel in bladders sleds
- 42% fuel consumption
- < 1% emissions of LC130s
- **$2.0M/yr net benefit vs. airlift**

Efficiency gains pay big-time!

- **12 bladders/tractor, net benefit increases to $4.7M**
- SPoT2 on packed trail?

Leader-follower convoys could double throughput

- 2 swings per fleet per year
- Will increase benefits but consume tractors faster

Cargo sled development

- Extra benefits for overweight & oversize cargo

Skunkworks: Autonomous Travel…

- Initial stages of development
- Leader-follower robotic technology
- Implement 4 robotic followers
  - Same 8-person crew, two 4-person shifts/day
  - Halve trip time
  - Enables two trips/season per fleet
- Can estimate incremental benefit/cost


Questions???