A Preliminary Ribbon Climber Design with Focus on Tribology and Fatigue

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The Goal:

- To design 230 construction climbers to increase the load capacity of the pilot ribbon to 20 tonnes in the least amount of time
- The first construction climber is limited to 900 kg
  - The drive train must weigh less than 233 kg
  - Climbers end their lives as counterweights for the ribbon

What can be accomplished here

- Show simple calculations that bound some of the critical design problems
- Evaluate the design shown in *The Space Elevator* by Edwards and Westling
  - compare to alternative proposal
- Identify critical material properties necessary to do a real design
- Begin to develop a 3D CAD model with possible components and place-holders

Baseline design from *The Space Elevator* by Edwards and Westling

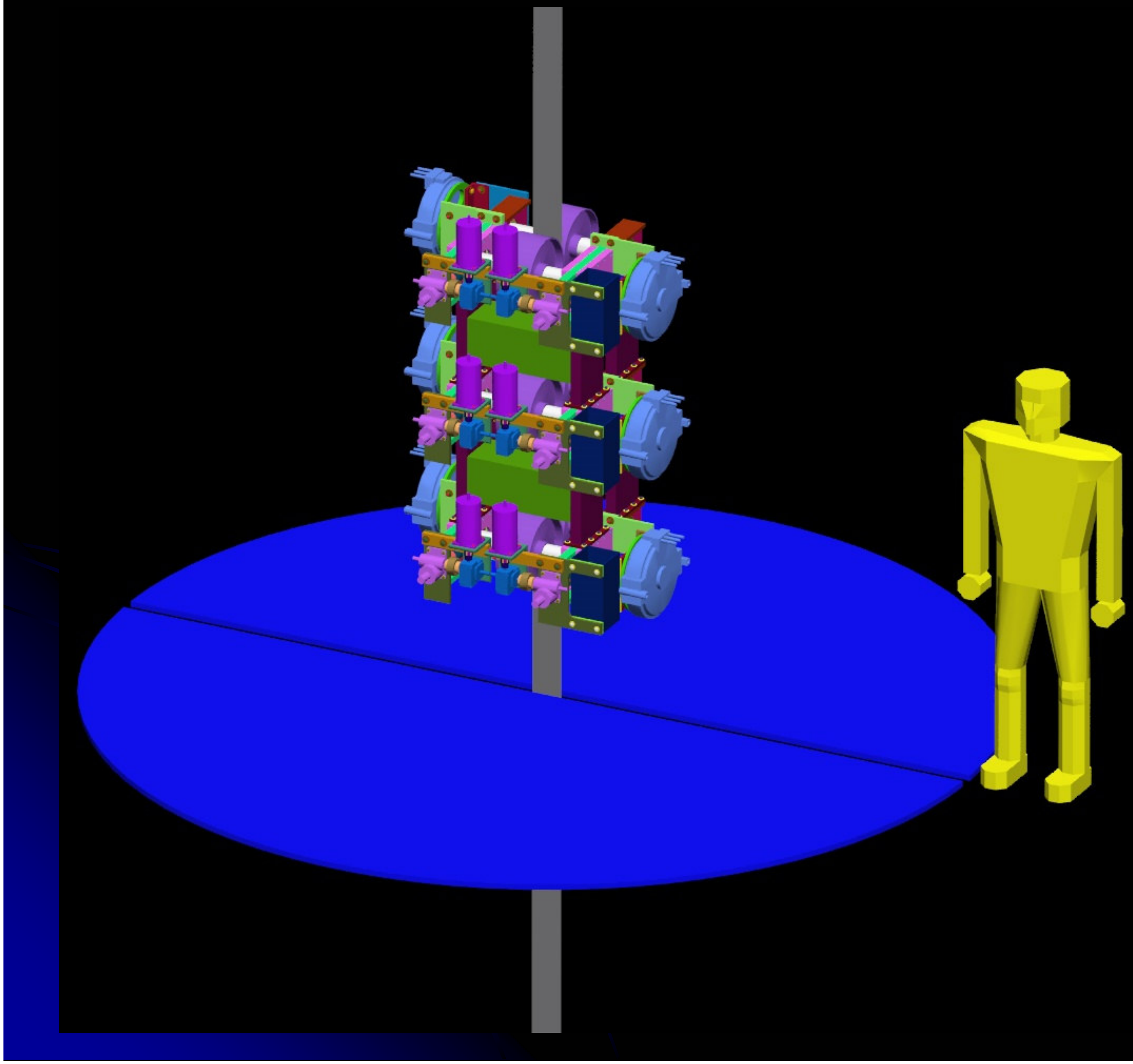
This picture comes from the gallery at http://www.isr.us/SEGallery.asp?m=6

This design needs a compression mechanism (not shown) to pinch the tracks together to the ribbon to produce traction

My objections to the baseline design

- Traction is only developed near the rollers
  - The straight section of the track in between rollers cannot contribute significantly to traction
- The belt is a very difficult problem from almost every design perspective
  - Flexure, fatigue and wear
  - Hysteresis and energy dissipation
- The track increases the rotary moment of inertia of the drive and mass of the climber slowing the drive down without adding traction

Proposed alternative design



Pinched wheel design with no track

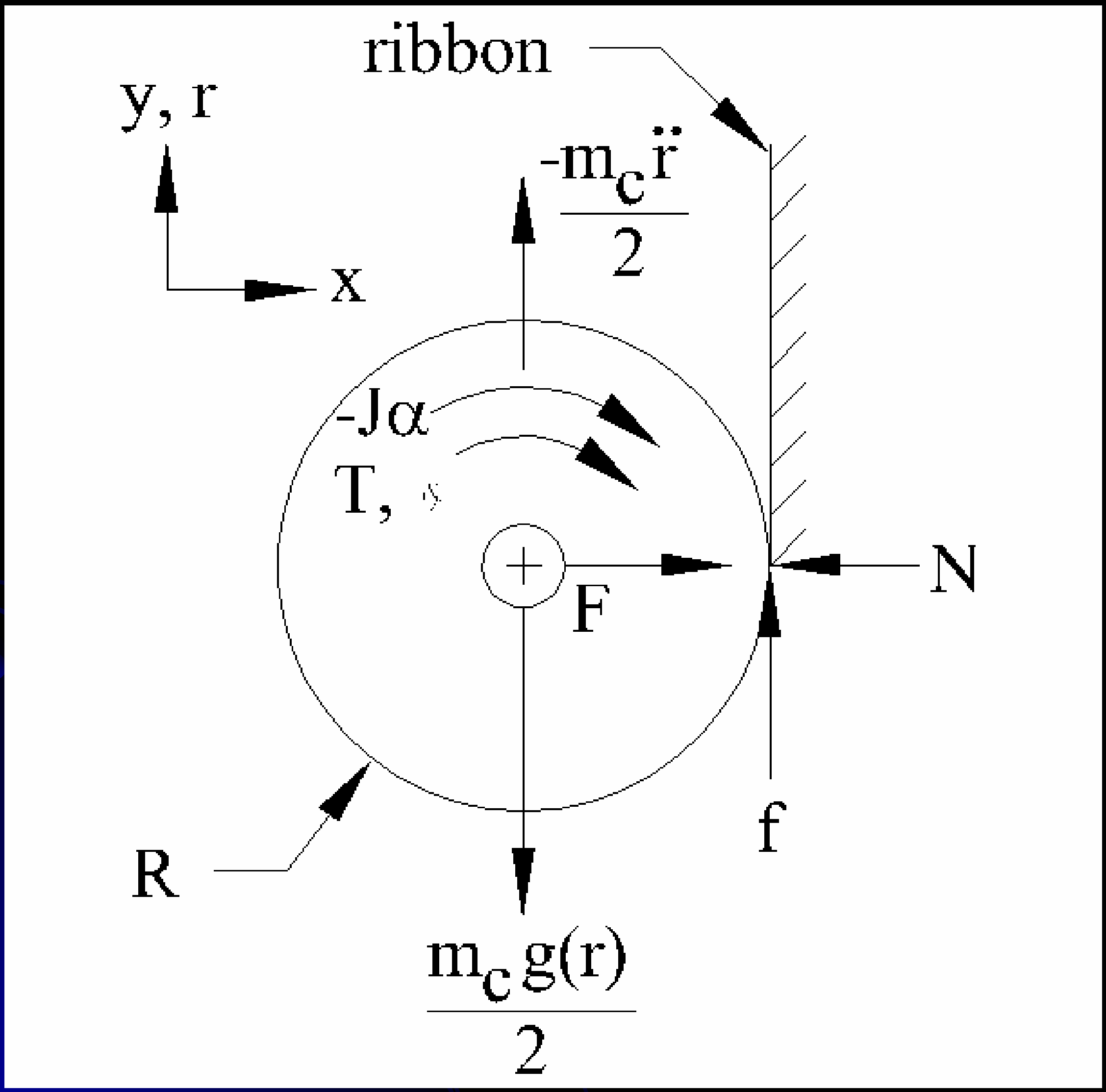
This is an incomplete scale model of the first climber. The PV array (blue disk) is 4 m in diameter

Not all components shown are space-worthy

Features in common between tracked and wheeled climbers

- Weight of climber limited to 900 kg
- Drive wheels and axles
  - Wheels drive tracks in tracked design
- Mechanism to compress wheels/tracks together to develop traction
- Motors totaling at least 100 kW power
- Structure that carries wheel and payload loads

Free Body Diagram of a Wheel



This picture models a single wheel on a climber with just two wheels, or it can be used to model the tracked drive as well by considering J as the rotary moment of inertia of the track plus its drive wheels.

f = friction force from ribbon

F, N are compression and reaction forces pinching wheels on opposite sides of the ribbon together

Summing the moments

$$\sum M = T - \frac{m_c \ddot{r} R}{2} - \frac{m_c g(r) R}{2} - J\alpha = 0$$

Rearranging terms to get the torque required to accelerate the climber:

$$T = \ddot{r}\left(\frac{J}{R} + \frac{m_c R}{2}\right) + \frac{m_c g(r) R}{2}$$

J is the rotary moment of inertia of the drive train

How does the track slow the climber?

- Power is delivered to the climbers by laser
- The first construction climber is limited to about 100 kW of power
- $P = T\omega = 100$ kW, so $T = 100$ kW$/\omega$
  - At $\omega = 0$, T_{max} comes from motor specs
- The torque is limited by the motors, so as J increases the acceleration of the climber must decrease
- J must be kept to a minimum!!!

Why is fatigue an issue?

- The space elevator is 100,000 km long
  - Construction climbers go the whole way
- A 20 inch diameter wheel must rotate almost 63 million times to get to the end of the ribbon—smaller wheel, more revs
- The climber gets traction by squeezing its wheels (or tracks) against the ribbon
  - The lower the coefficient of friction between the wheels and ribbon, the harder the climber must squeeze

What is the relationship between friction and fatigue?

- The coefficient of friction between the wheels/track and ribbon determines the stress state in the whole drive mechanism
  - Lower coefficient of friction $\rightarrow$ harder the climber has to pinch the ribbon
  - This coefficient is currently unknown and is a critical material property for design
  - The wheels and axles are in fully reversed contact or bending stress
- Fatigue failure is the result of cyclic stress

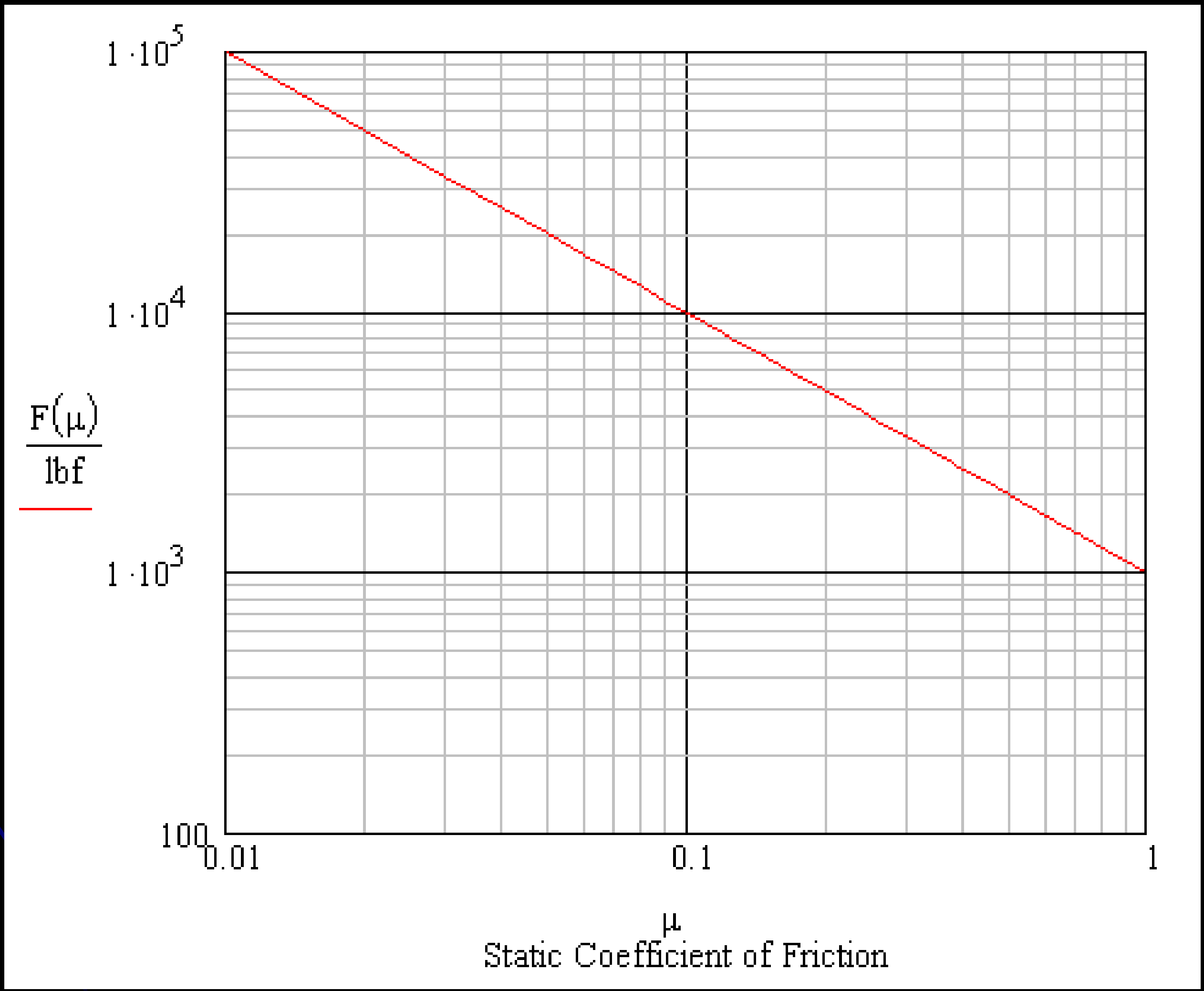
What are fatigue failure modes of concern?

- Cracking a wheel axle
  - a disastrous failure for a climber
- Rolling fatigue causing spallation of sharp metal chunks from the rim of the wheel
  - A potential disaster for both ribbon and climber
- We need ~100% confidence that a climber will make it to the end of the ribbon
  - Fatigue allowables are always expressed at 50% confidence of failure
  - Allowable stresses are reduced to increase confidence

How does wheel pinch force vary with μ?

$$F(\mu) = \frac{m_c g(r)}{2\mu}$$

This graph and equation gives the total force required to pinch either wheels or tracks together around the ribbon to just keep a 900 kg climber from sliding down the ribbon



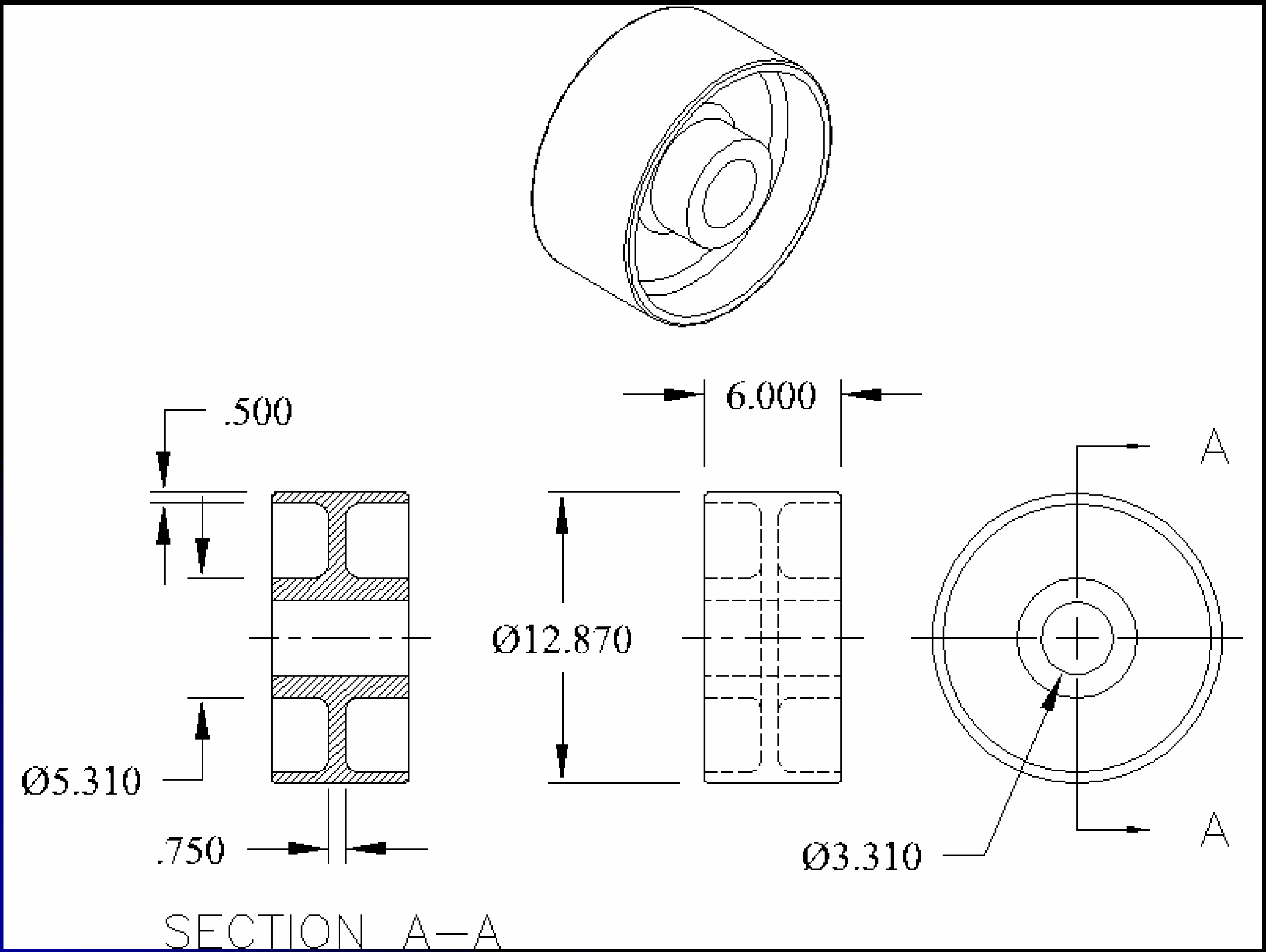
The implication of the last graph

- If the static coefficient of friction is as low as 0.1, wheels or tracks on a 900 kg climber must be compressed together with a total force of 10,000 lbs (5 tons)
- μ = .1 is right in the middle of the expected range for coefficient of friction
- Lower μ would make the ribbon too slippery for traction
  - $\mu < 0.1$ is characteristic of sliding bearing materials

Conclusions from stress analysis

- Larger wheel diameters reduce contact stresses for fatigue
  - Larger wheels increase the climber's mass
- Adding wheel pairs lowers force on each pair, makes wheels smaller
  - Climber weighs less up to a point
- The maximum number of wheel sets is three and minimum wheel diameter is ~8.4 inches to rotate fewer than 150E6 revs
  - Fatigue allowable must be high to make small wheels

First, simple wheel design

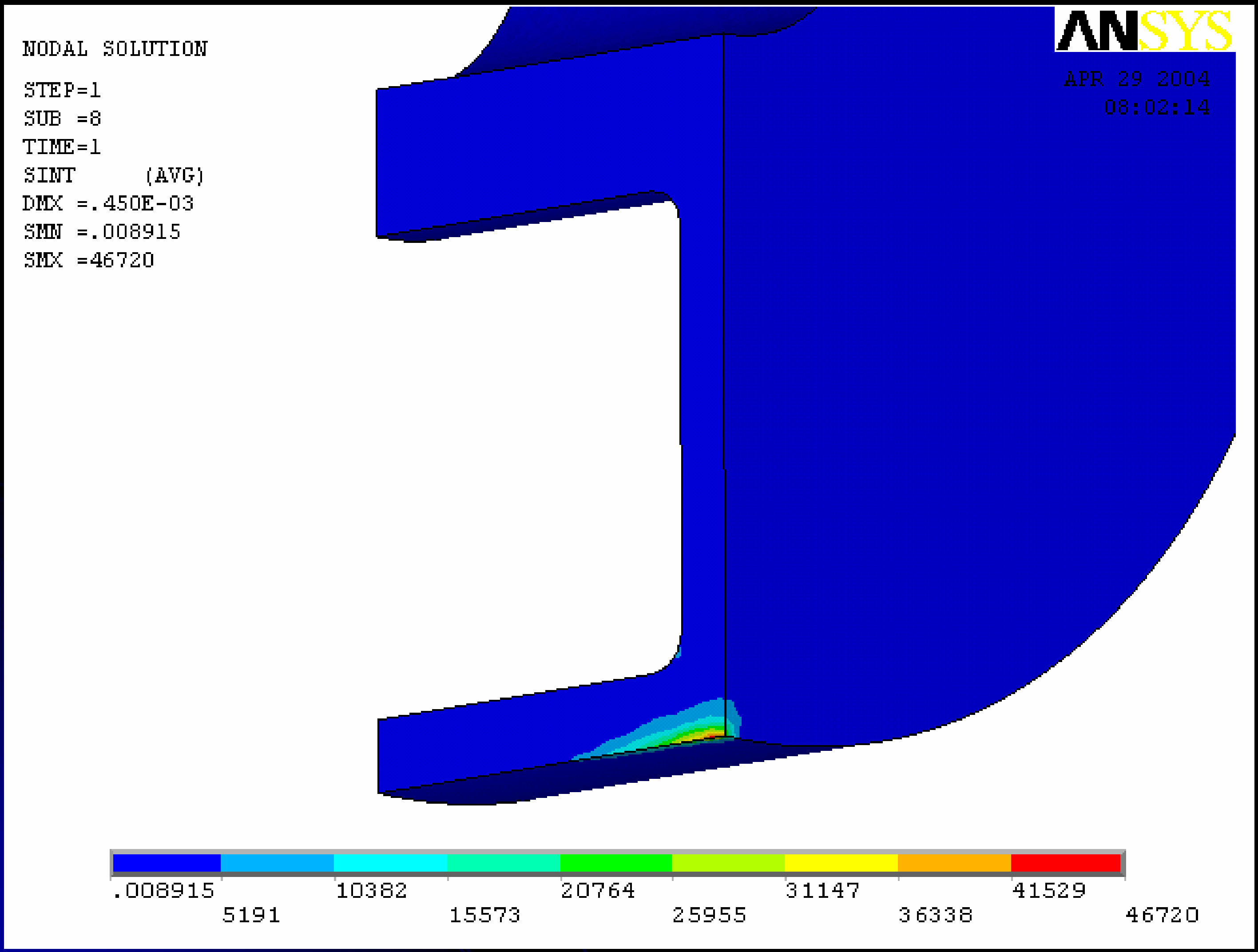


First guess at a wheel design for a three-pair climber

Original material selection was Stainless 321, but Ti-8Al-1Mo-1V has a much higher fatigue limit.

Wheel was too heavy for mass budget—35.5 kg/wheel, 213 kg for 6.

FEA analysis of first wheel



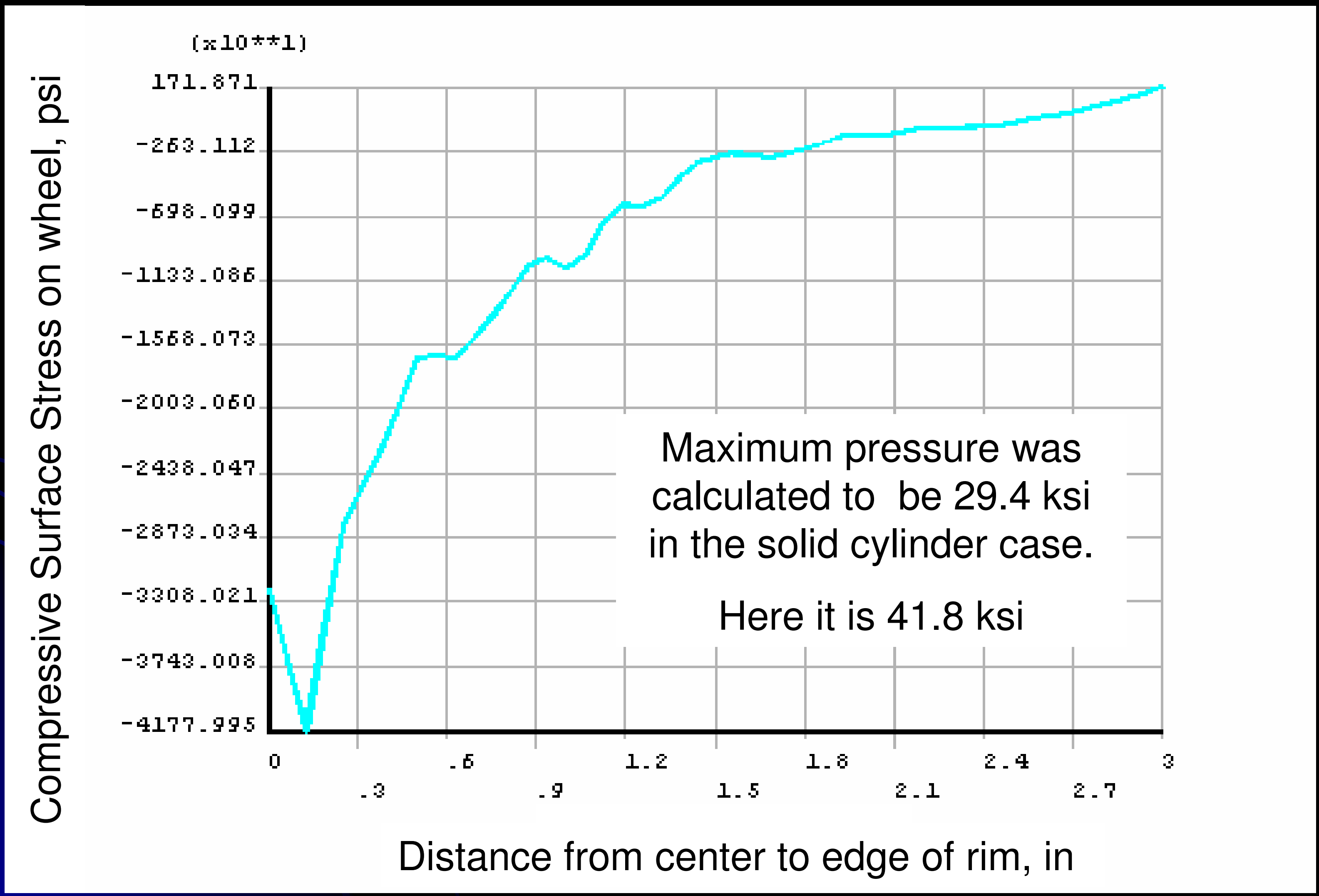
Quarter model of the wheel, stresses are in psi.

Contact stress with ribbon is concentrated near hub disk.

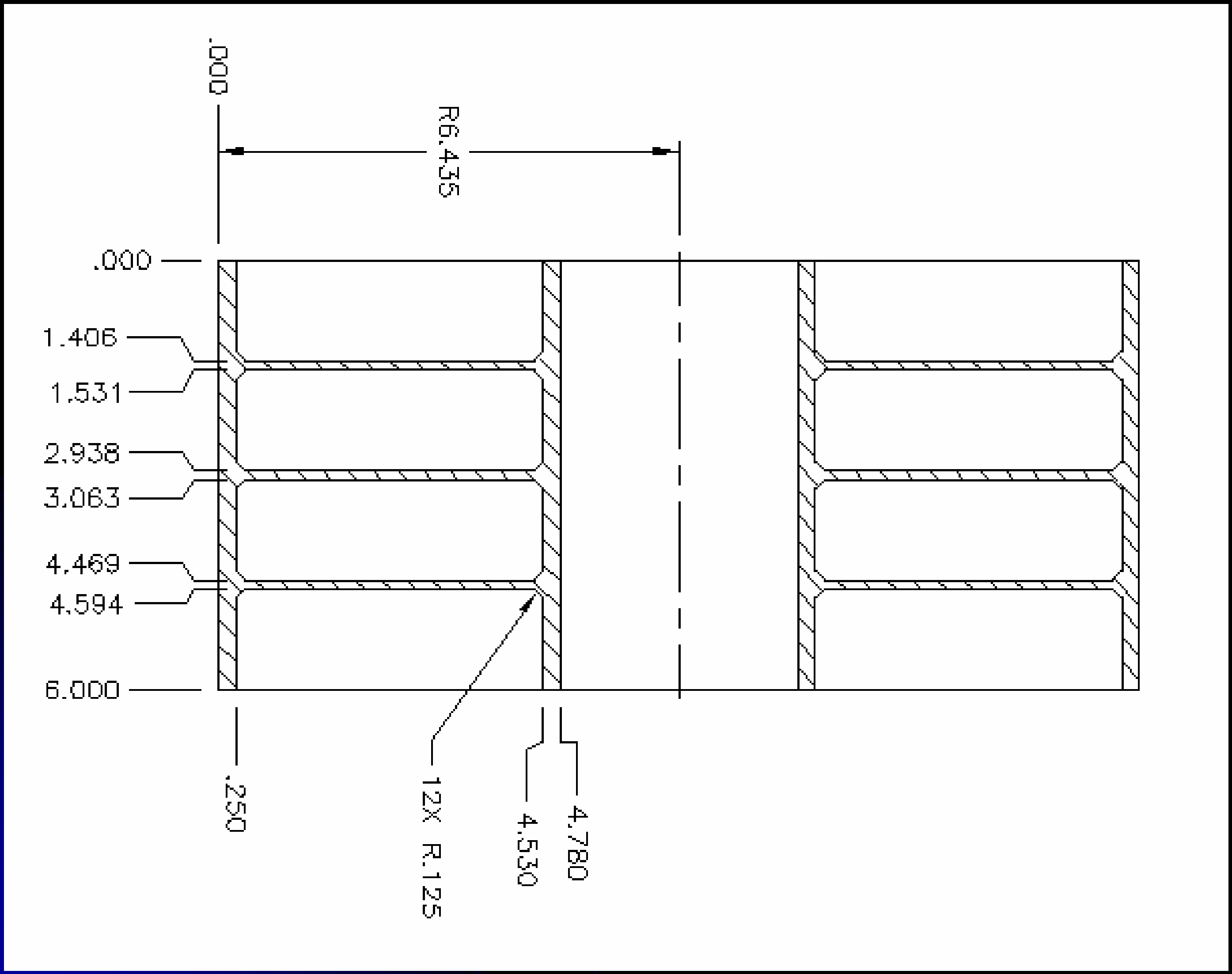
Outer edge of rim does not contribute to distributing the compressive load from the axles.

FEA courtesy of Robert Wands

Compressive stress vs. distance along rim in quarter FEA model



Second wheel design



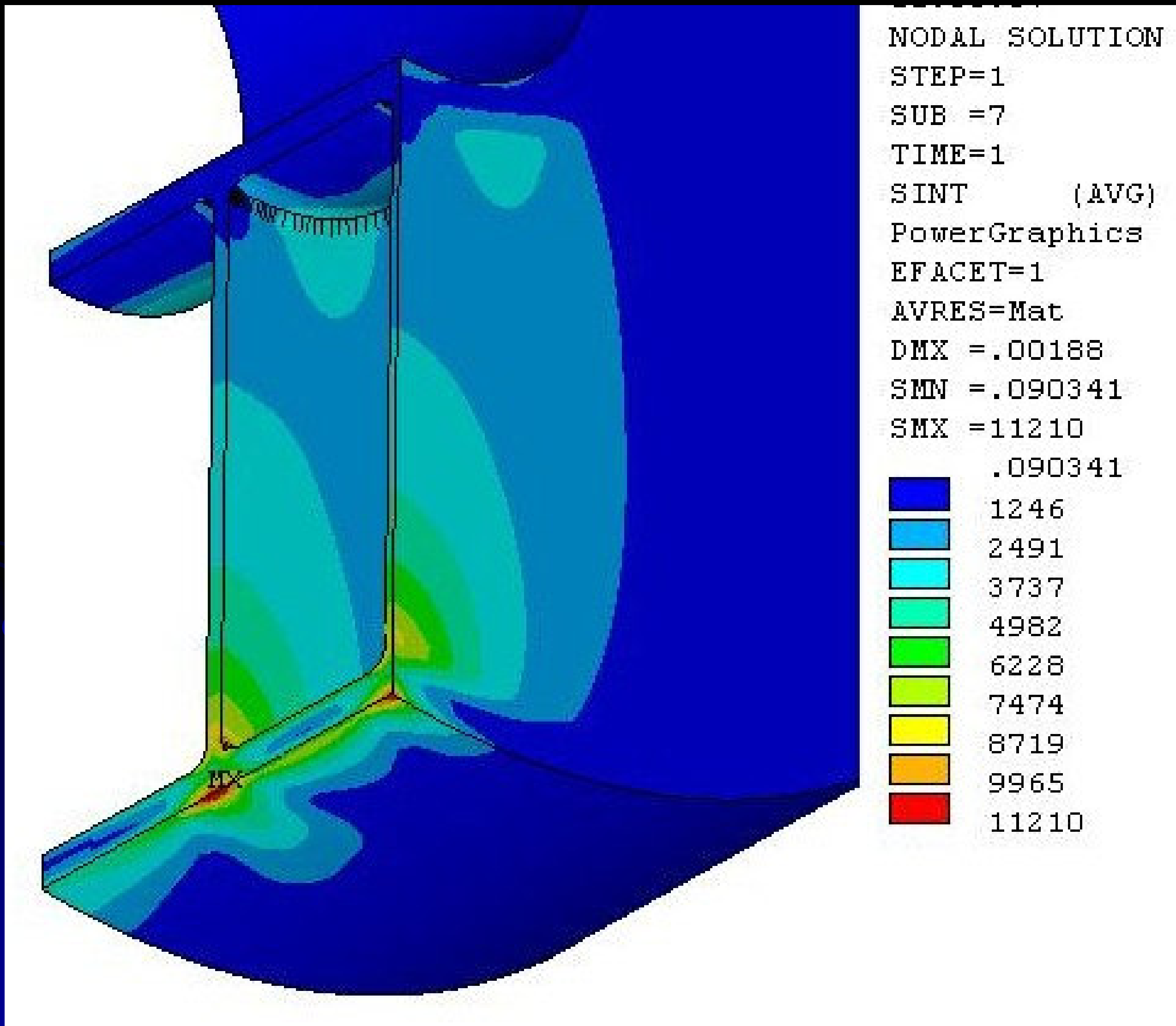
This wheel has three central disks to better distribute load along the rim.

Material is Ti-8Al-1Mo-1V. Fatigue allowable at 50% confidence is 92 ksi.

Mass of one wheel is 8.8 kg. Six wheels are 52.8 kg.

This is lighter than before, but the mass budget is very difficult to satisfy.

FEA on new wheel design

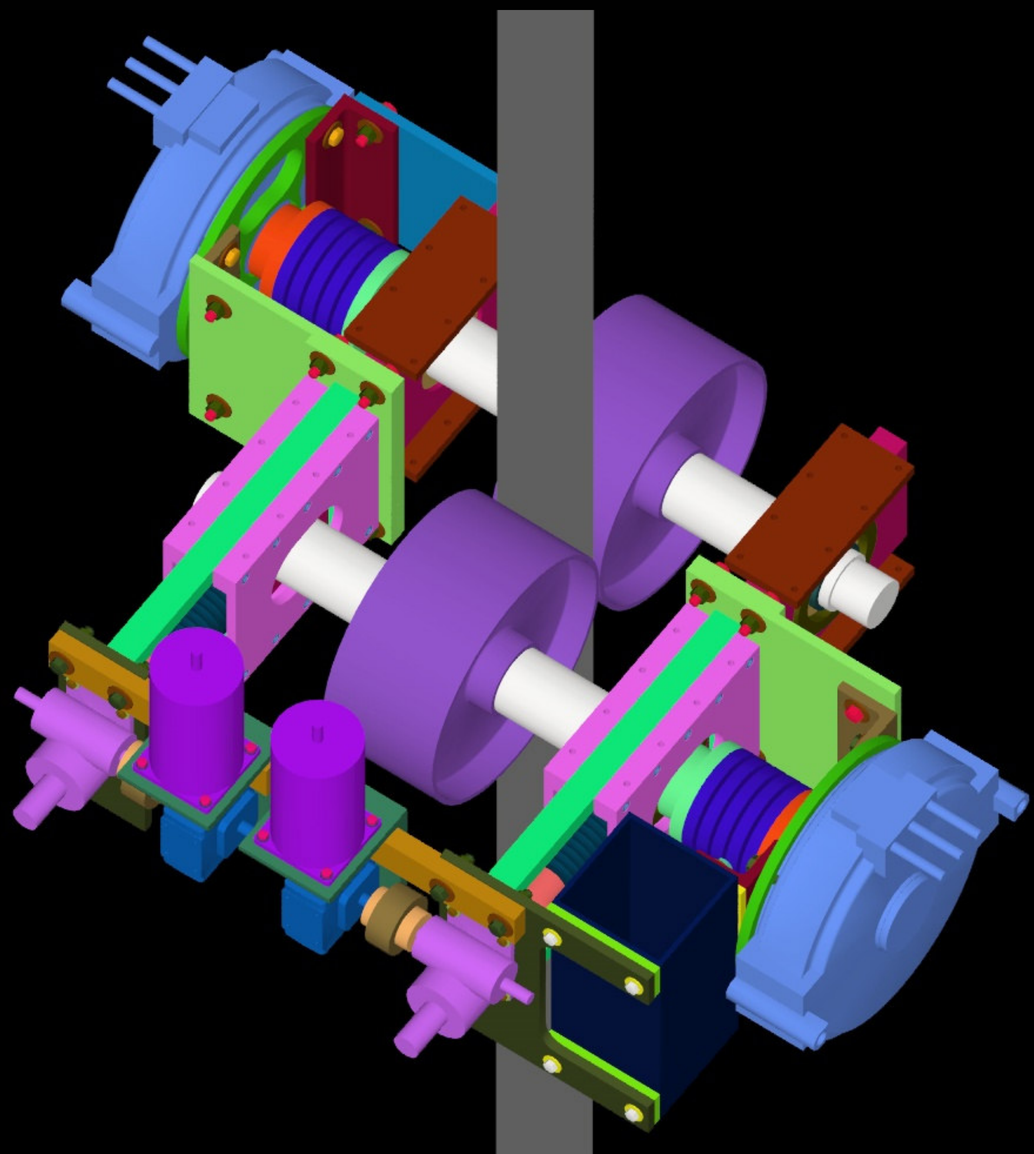


- This design has 3/8 of the contact stress of the solid cylinder case calculated by hand from Hertzian contact stress equations
- Note the wider zone of contact
- Stress is well within allowables
- Further weight reduction looks possible
- FEA courtesy of Bob Wands

Development of the CAD model

- Goals for the model:
  - to identify all the features of the drive train and associate real components with them even if they were just placeholders
  - to see if reasonable components would fit within the mass budget
  - to address assembly considerations
  - to minimize structural mass by placing material primarily in the load paths

Two wheels clamped onto the ribbon

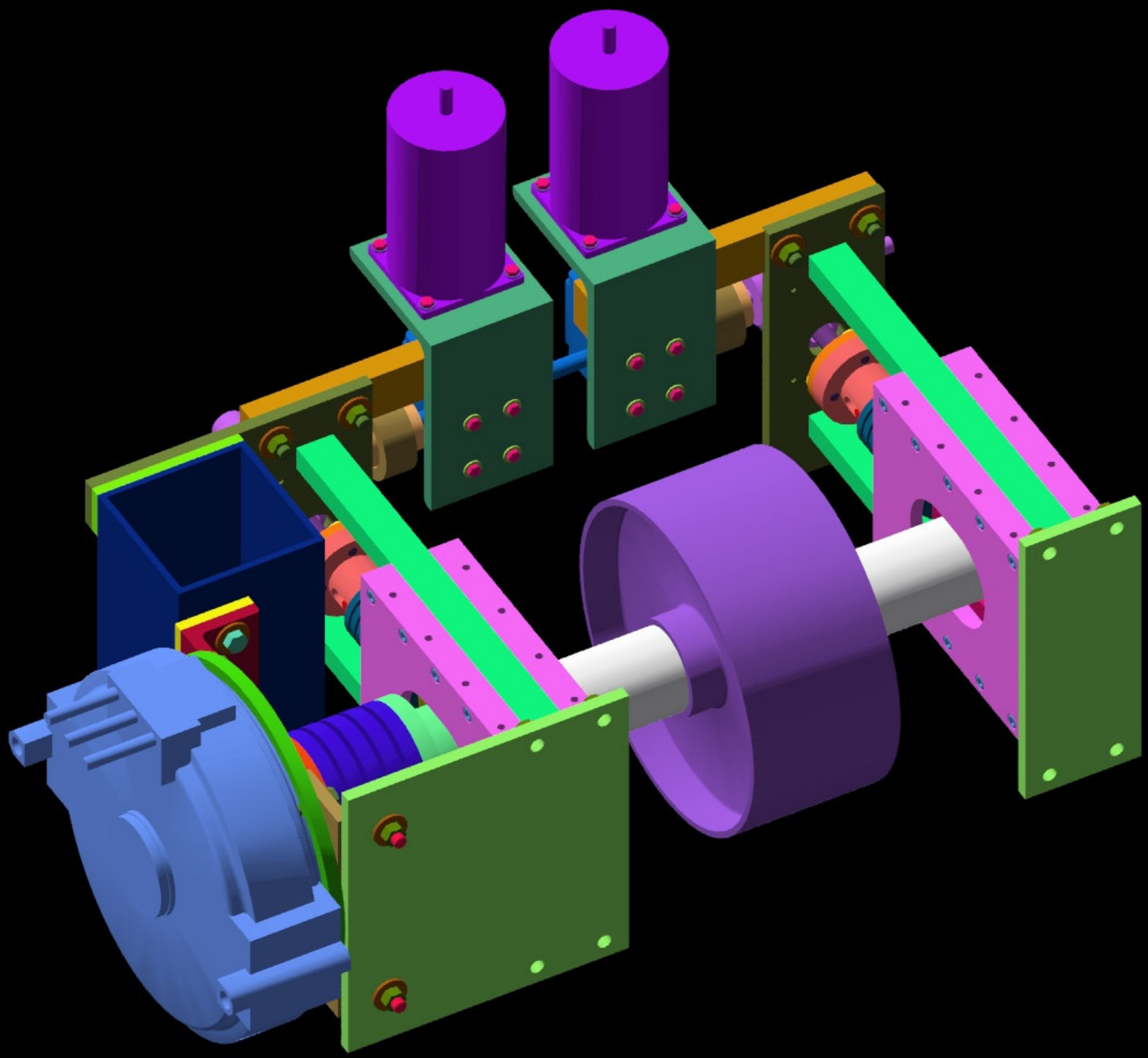


The axle on the far side of the ribbon is fixed to the frame of the climber through self-aligning bearings.

On the near side of the ribbon, the axle is mounted on a linear slide so the wheel can be pressed against the ribbon or retracted away from it.

Motors are connected to the axles by Schmidt couplings to absorb any angular or lateral offsets.

Floating axle traction module



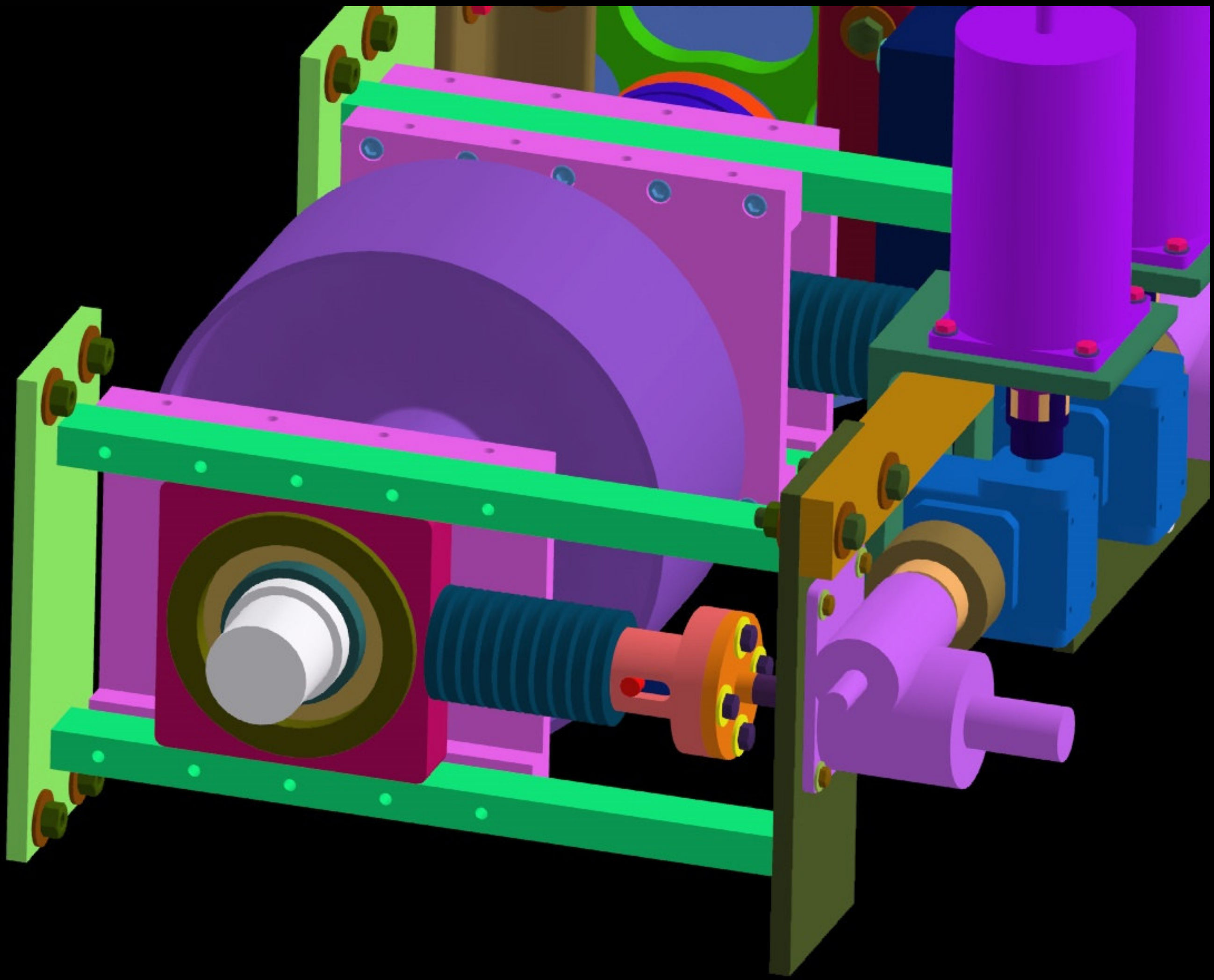
The two sides of this module are not stable to torsion without the interface structures between modules

Wheel pinch forces are transmitted through the light green plates on either side of the wheel.

Forces coming from the rest of the climber are connected through the bearing housing slides

Every wheel is motorized.

The wheel compression mechanism

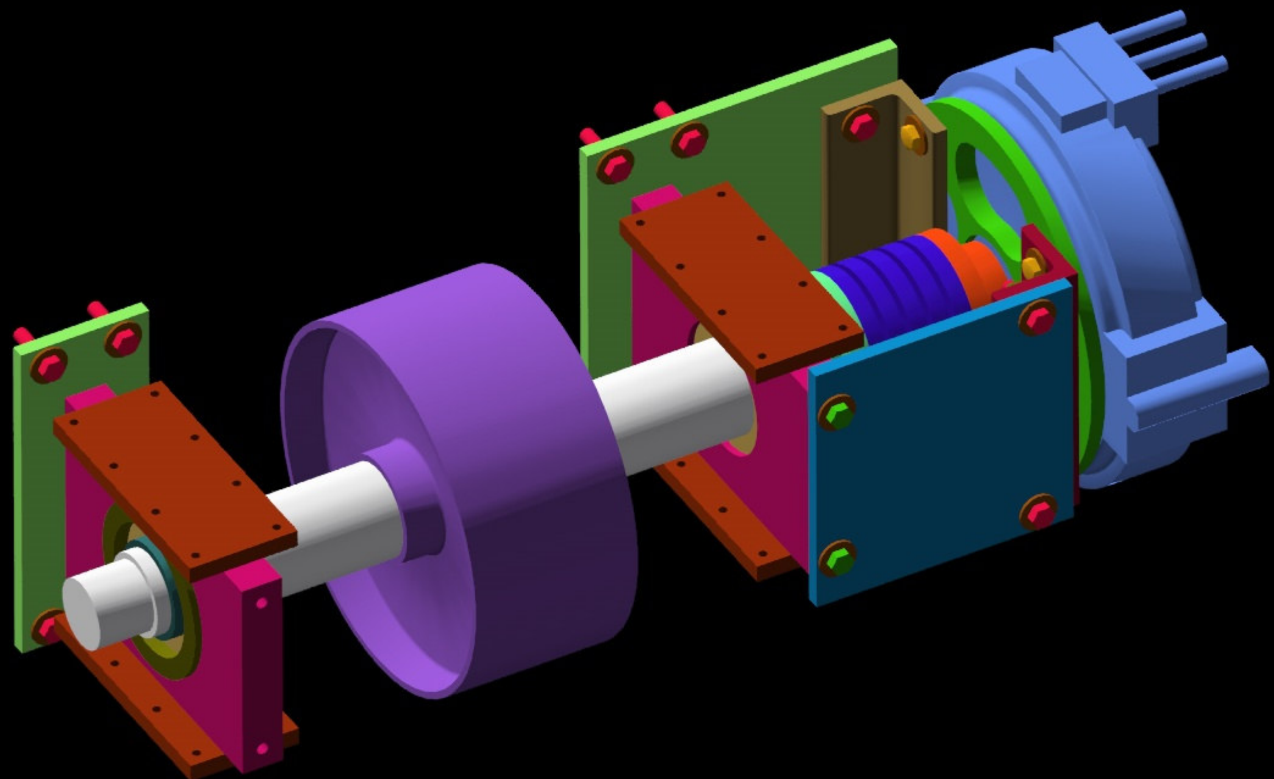


One ton screw jacks compress a stack of belleville washers

This concept allows great resolution in the application of force to the axle

The components were all sized to take the loads but are not space-worthy. A concern is whether space-worthy components are even larger.

Fixed axle traction module

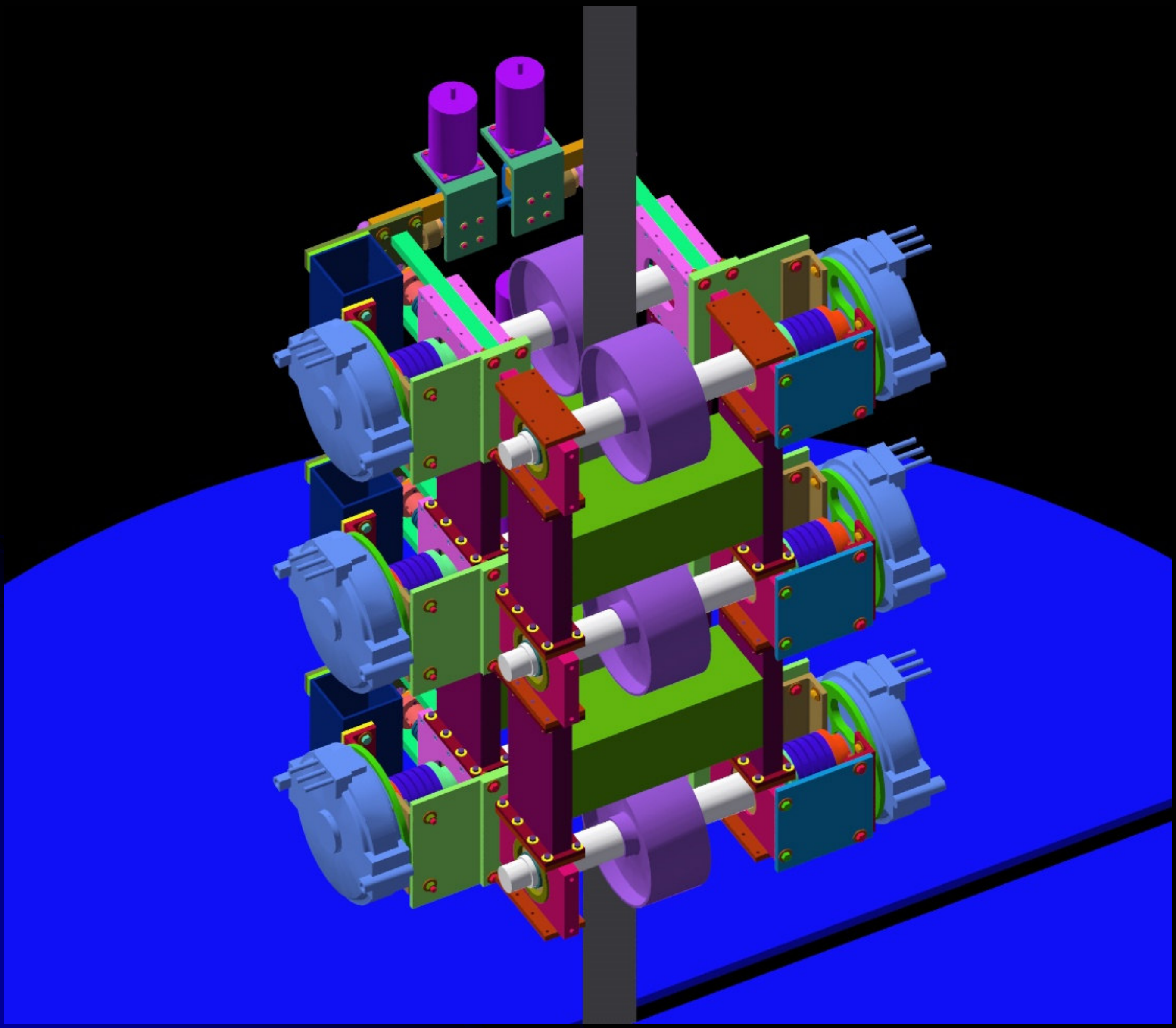


This module drives a wheel and absorbs the compressive force coming from the wheel on the other side of the ribbon.

This module is lighter than the one on the other side so balancing a climber to force the CG to lie within the ribbon is an issue.

Motors shown are 50kW axial gap models from Precision Magnetic Bearings.

Interface structures



The structural modules in between the traction modules give torsional stiffness to the traction modules and allow loads from the rest of the climber to be coupled to the drive train.

This drive design (not including the PV arrays) weighs 1625 lbs, or 737 kg. This is about 3.16X the allowed 233 kg for the drive train. 20kW motors reduce it to 647 kg, or 2.77X.

Mass Breakdown of components

Description of climber components:	Climber with six 20 kW motors	Climber with six 50 kW motors
Mass of 12 self-aligning bearings, kg	16	16
Mass of 6 axles, kg	32	32
Interface structural material, kg	51	51
Mass of 6 wheels, kg	53	53
Mass of 6 Schmidt couplings	63	63
Mass of structure in 3 fixed axle modules, kg	71	71
Mass of 6 motors, kg	84	174
Mass of 3 pairs of compression mechanisms, kg	136	136
Mass of structure in 3 floating axle modules, kg	141	141
Total mass of climber traction drive only, kg:	647	737
Required drive system mass, kg:	<233	<233

Motor masses courtesy of Rick Halstead, Empire Magnetics

Climber Mass distribution from *The Space Elevator* by Edwards and Westling

Table 3.2: Mass Breakdown for the first climber

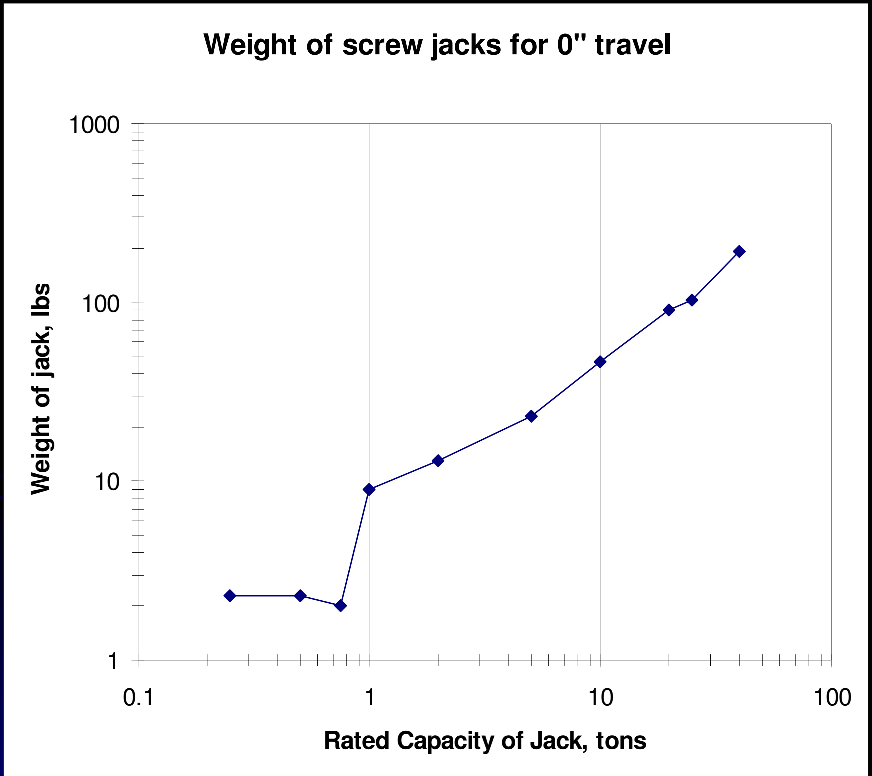
Component	Mass (kg)
Ribbon	520
Attitude Control	18
Command	18
Structure	64
Thermal Control	36
Ribbon Splicing	27
Power Control	27
Photovoltaic Arrays (12 m^2, 100 kW)	21
Motors (100 kW)	127
Track and Rollers	42
TOTAL	900

Design constraint of <233 kg comes from adding the red numbers in the table.

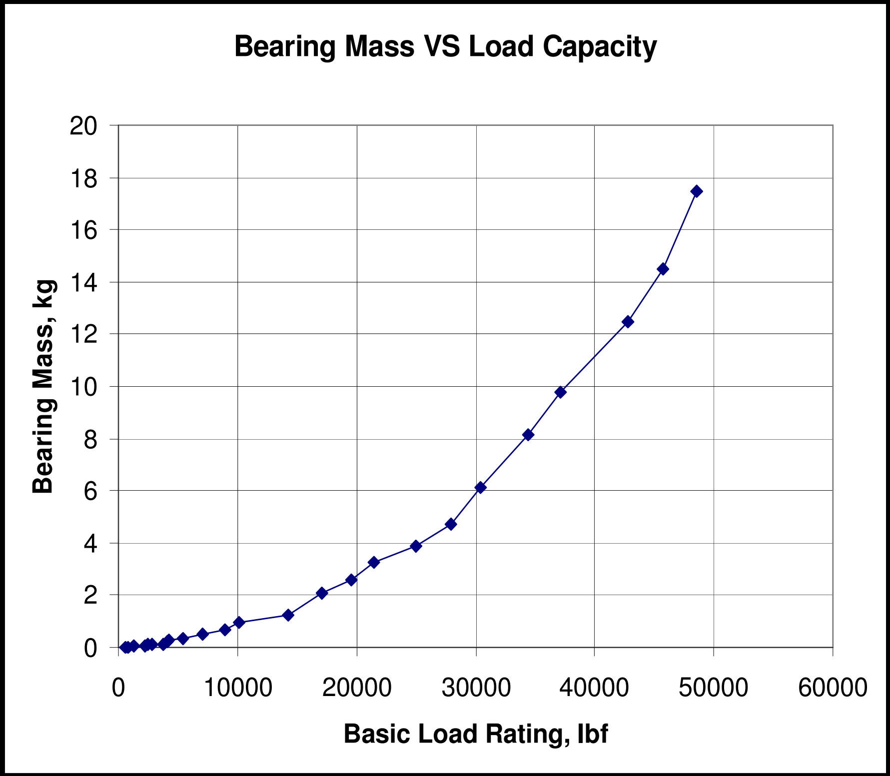
Not all of the structure can be dedicated to the drive system.

How components scale with capacity

Templeton-Kenly Uni-Lift Screw Jacks



SKF Self-Aligning Ball Bearings



The implication of these graphs is that there is a “threshold” mass for components at the low end of capacity and that mass increases rapidly with capacity

Conclusions

- The design shown is too heavy and needs to be made space-worthy
- Many components still need design:
  - thermal management system
  - brakes
  - power distribution/control hardware
  - batteries (?)
- Friction between the wheels and ribbon controls the stress in the whole drive train
- Fatigue is a killer issue requiring much analysis

Conclusions continued

- This design shows potential solutions for how to compress the wheels together and couple motors to the axles
- The pinched wheel design may apply higher compressive stress to the ribbon than the track design
  - Only complete designs and analyses will tell
- The pinched wheel design should be lighter than the track design, cheaper to build and able to accelerate faster

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