Permanent Magnet (PM) Induction Heater for Paraffin Abatement

DOE-SBIR Phase 2B

April 2022 – March 2024

Budget: 1,044,929

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Problem Statement: Motivation

- There are an estimated 1.7 million oil and gas wells in the United States.
- 771,000 of these are considered marginal producers[1].
- Combined they make up 11.3% of the US oil production and 8.3% of the US gas production.
- In that last 10 years, over 131,000 of these oil wells and 48,000 gas wells have been plugged and abandoned.
- Most of these wells suffer from paraffin plugging problems.
- Extending the economic life of these wells provides the US with energy security with the lowest carbon footprint.

1 http://info.drillinginfo.com/stripper-wells-enhanced-oil-recovery-eor/

Current Methods for Removing or Preventing Paraffin Formation

- Hot oiling: This is the most common method that involves heating stock tank oil and pumping it down the tubing or annulus.
- Hot water: Injection of hot water to melt the paraffin.
- Paraffin inhibitors: Not very effective and quite expensive when used long term.
- Mechanical scrapers: Can cause damage to tubing and is not very effective at removing all the paraffin.

Advantages of our Permanent Magnet Induction Heater

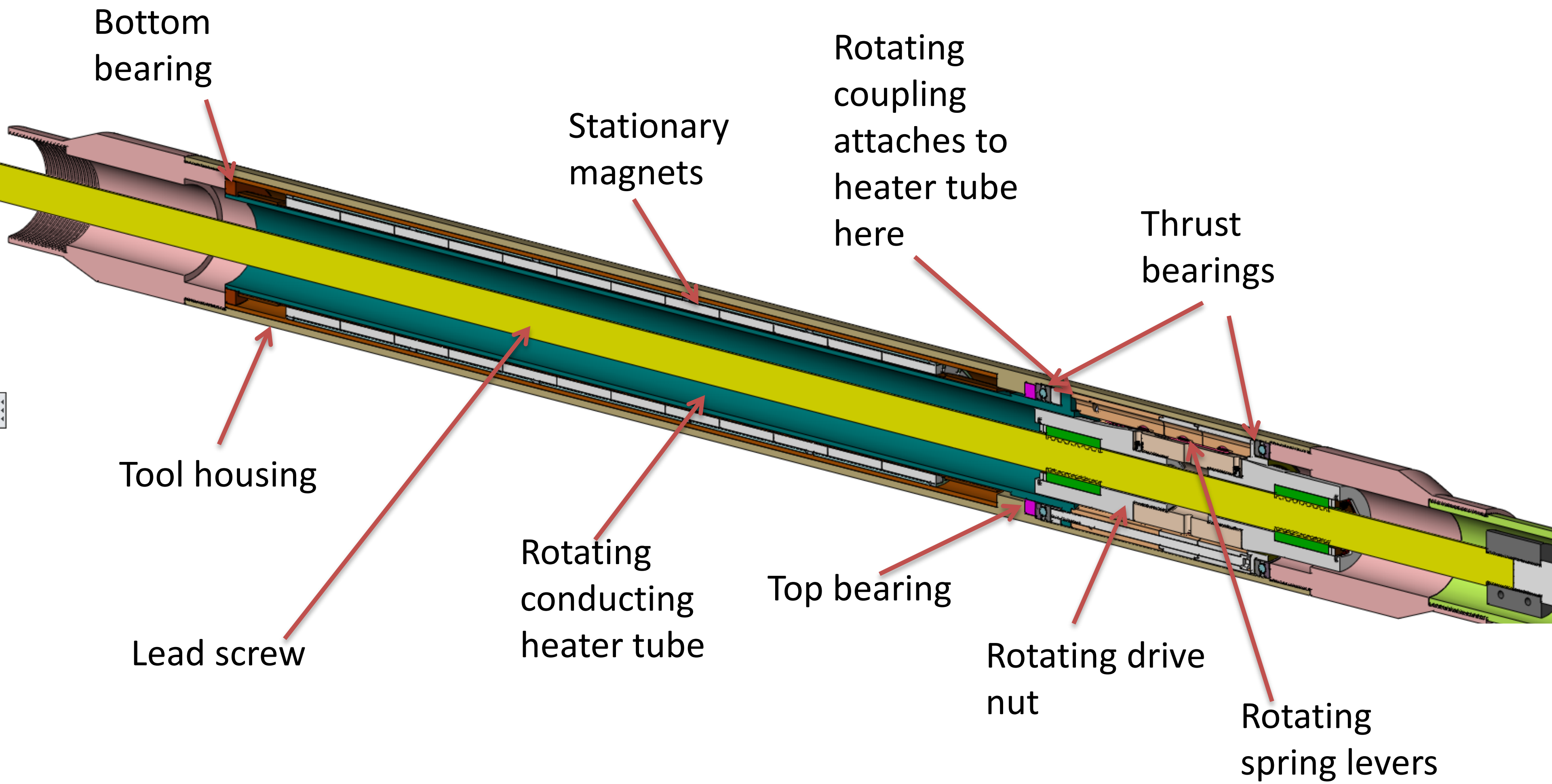
- Preventive: The method prevents paraffin from forming. It is much harder to remove paraffin one it is formed. This reduces production decline rates.
- Efficient: The heating is provided at the location where it is needed. The entire wellbore is not heated.
- Simple and noninvasive: No electrical wires.
- Integrates with existing hardware: Can be screwed into the tubing and the sucker rods.
- Inexpensive: The incremental cost of the tool is relatively small.
- Long life: The device can be replaced or repaired only when the tubing is pulled for routine maintenance or a workover.
- Provides continuous heat into the hydrocarbon flow to prevent paraffin formation.
- Can be positioned at an optimal depth or at more than one location to prevent paraffin formation.
- No special equipment needed: The lead screw and back driven nut integrate into the rod string and engages the rotating conductor with quick connect couplings and no further equipment is required to operate the device
- Allows pump seating and service with conventional techniques.

Example of Economic Drivers for Onshore Wells

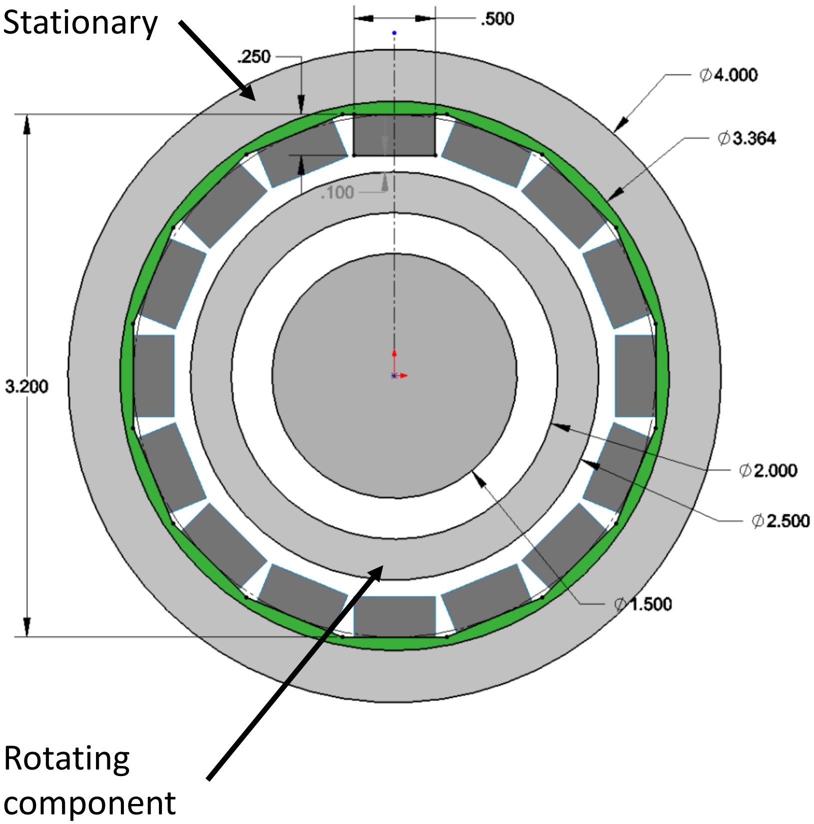
- Higher continuous oil production.
  - Less decline in production (no choking of tubing with paraffin buildup)
  - No formation damage. No paraffin being squeezed into the perfs (as happens in hot oiling).
  - Average incremental production of 5 BOPD (5bbl*$45/bbl*365days = $82,125 additional revenue)
- Lower annual treating costs than hot oiling
  - Annual cost of hot oiling = $5,000 /year/well
  - Down time + oil burned ($45*50 bbl/year) = $2,250 /year/well
- Tool cost = $30,000 per tool (purchase) or $10,000 /year on lease.
- Operating costs (electricity): 4KW *365*24*0.05$/KWh = $1752 /well/year.
- **Total annual revenue increase: $77,623 /year/well**

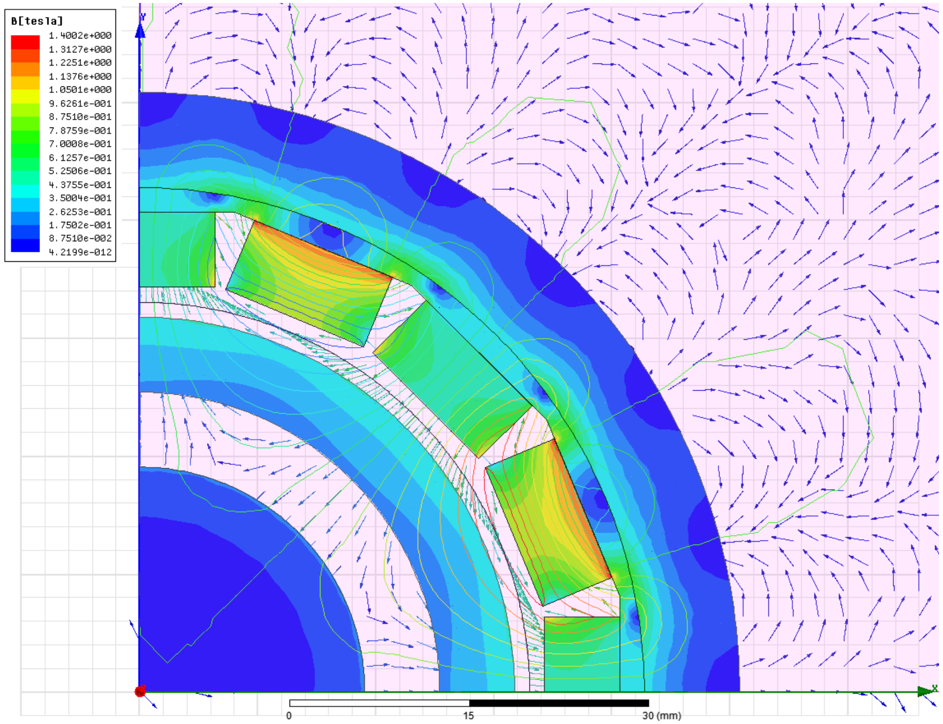
***Disclaimer: This is only an example, actual costs and revenues may differ.**

Paraffin Heater & Coupling
--24" Test Heater--



Configuration and Magneto-Static Flux Plot

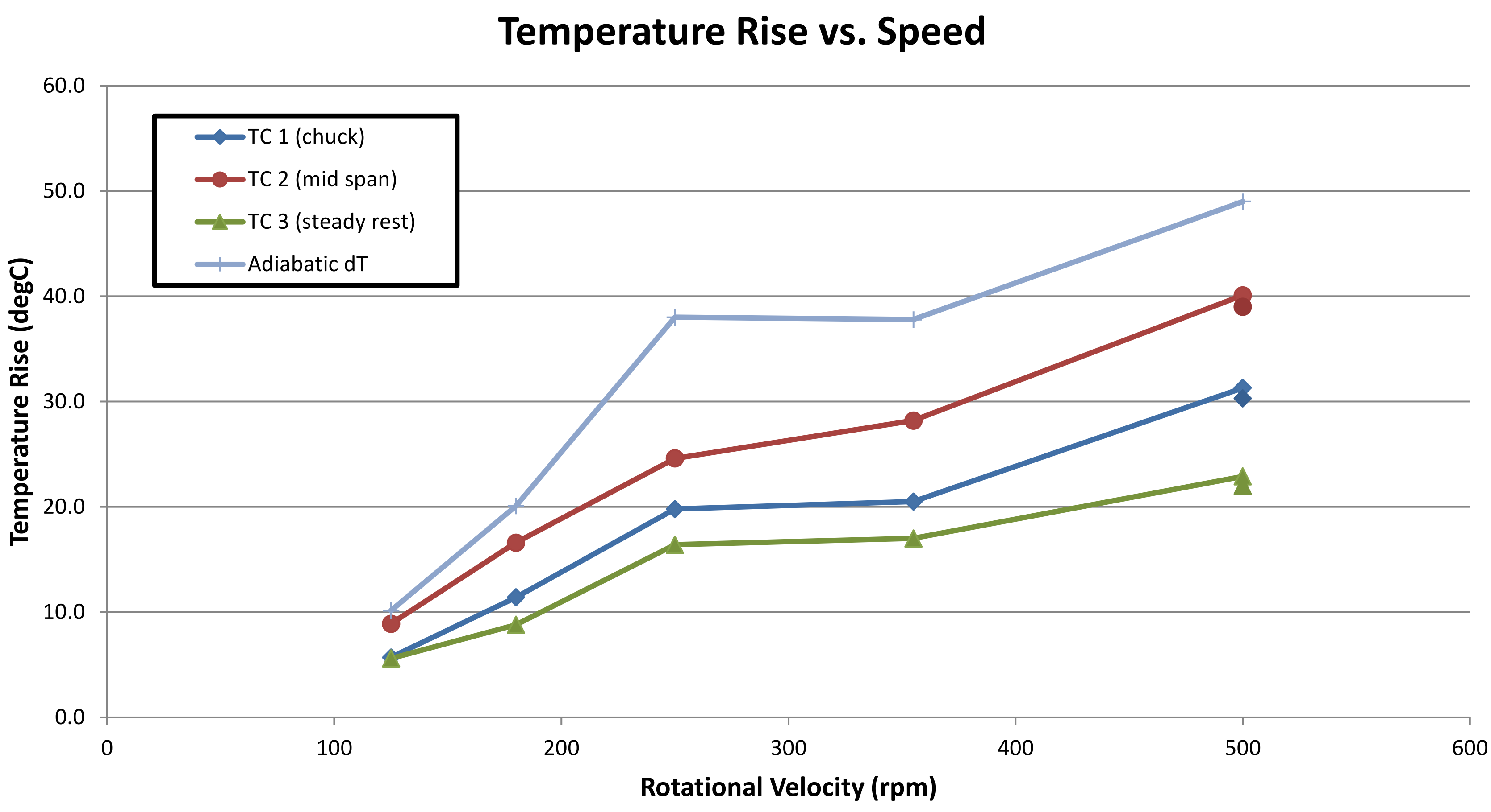




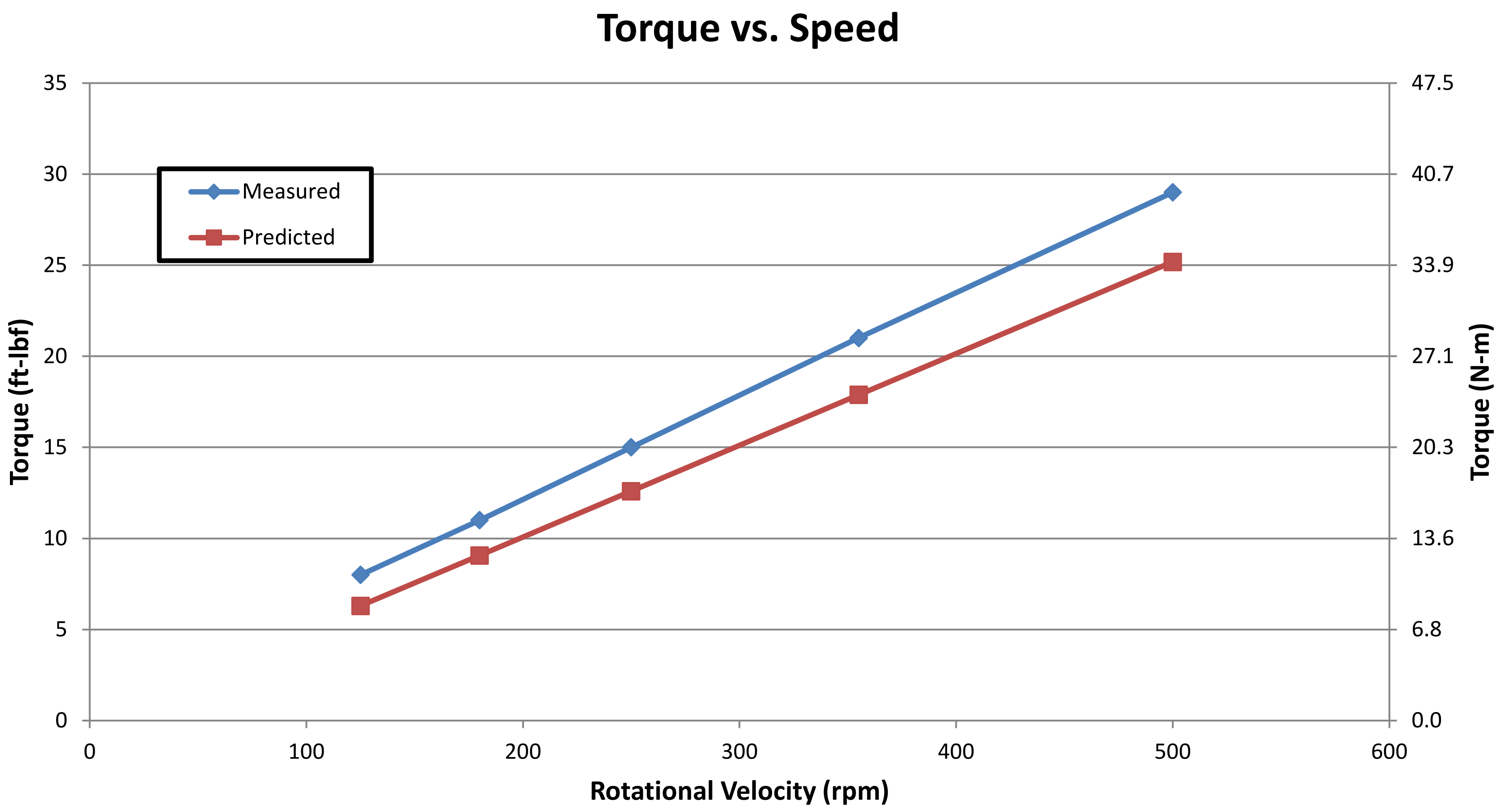
Heat Generation

- 4230 W/m power loss @ 600 RPM
- 67.2 Nm per m reaction torque

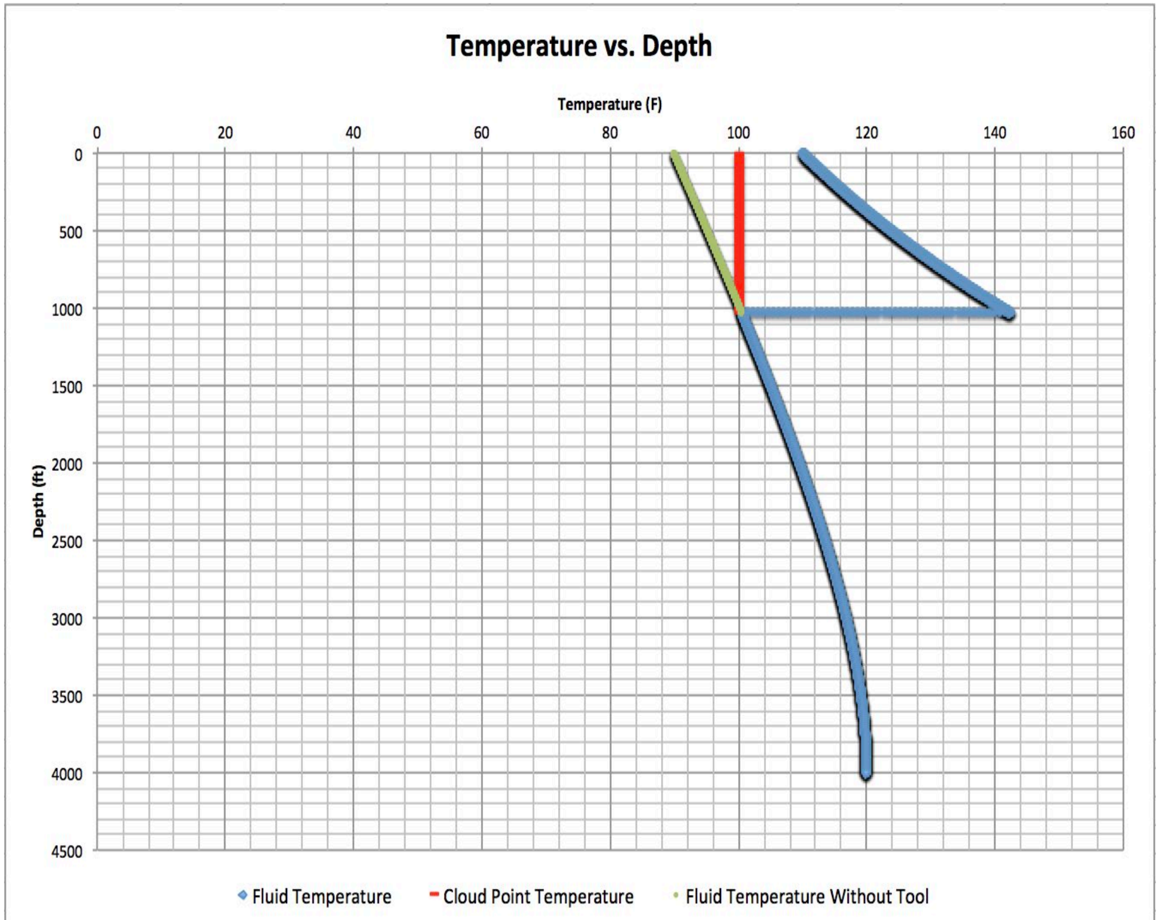
Test Results



Test Results



Computer Program to Estimate Heater Requirements for a Well



Heater Installation Procedure

- Pull sucker rod string and pump
- Pull tubing to planned installation depth
- Install heater unit in tubing and reinstall tubing
- Reinstall pump, seat pump or “tag” and mark sucker rod at surface as reference.
- Pull sucker rod and install lead screw/coupling spool using short rod lengths to set tool stroke consistent with pump stroke.
- Install remaining sucker rods and polished rod and reattach to pump jack

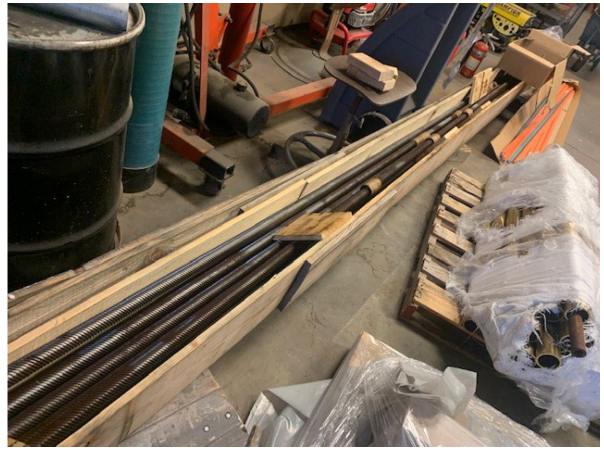
Paraffin Heater Tools Built

Tool #	1	2	3	4	5	6	7
Tubing Size	2-7/8	2-3/8	2-3/8	2-7/8	2-7/8	2-7/8	2-7/8
Coupling Type	Friction	Self-Starter	Snap-In	Snap In	Snap-In	Snap-In	Snap-In
Lead Screw Size	1X2 X 10'	1-7/8 X 4 X 23'	1X2 X 14'	1-7/16" X 3 X 23'	1-7/16" X 3 X 23'	1-7/16" X 3 X 23'	1-7/16" X 3 X 23'
Status	Installed 8/19 Removed 9/19	Installed 4/21 Removed 5/22	Installed 8/21	Installed 9/21 Removed 1/22	Ready for Assembly	Ready for Assembly	Ready for Assembly
Location	Electra Layline Energy	Eagleford RW Dirks	West Tx NEIAB	Wyoming Merit Energy			
Well/Tool Depth	2600/66	11k/5000	5000/2000	5000/500			

Components to be used for Gen III design (tools 5–7)

Parts Inventory

Steel tubes



1” & 1-7/16” lead screws

Coupling Parts

Heater Assemb. & Cross Overs

Brass Tube Stock

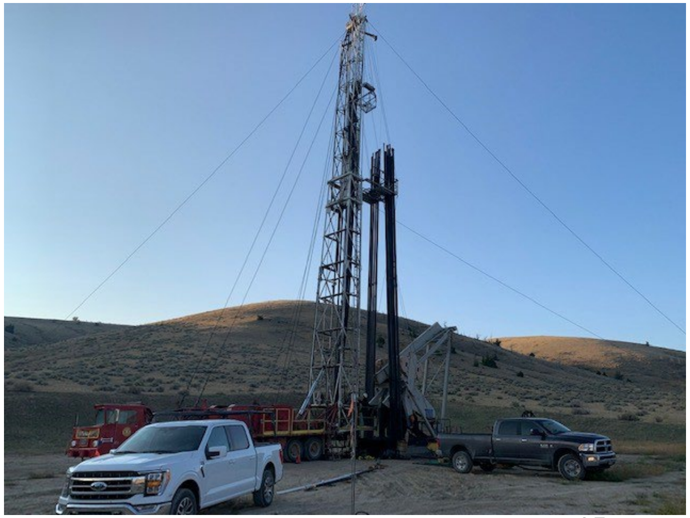
Brass Tubes Finished

Paraffin Heater Program

Layline Energy
Electra, Tx—8_19

RW Dirks
Karnes City, Tx—4_21

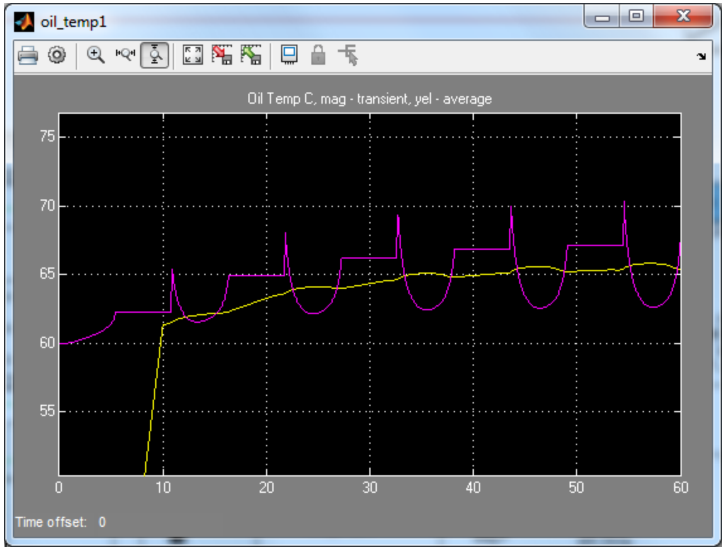
North East IAB
Robert Lee, Tx—8_21



Merit Energy
Meeteetse, WY—9_21

Field Test #1—Electra, TX
Layline Energy (Aug. 2019)

- 2-7/8” tubing 1” X 2 lead screw X 10’ long
- Tool depth: 66’
- 54” stroke length
- 6.5 strokes per min
- 104 bbl/day (2 bbl/day oil & 102 bbl/day water)
- Predicted:
  - Ave horsepower required: 1.6hp
  - Sucker rod force +/- 800 lb
  - Sucker rod torque +/- 14 ft-lbs
  - Ave temperature oil temp rise 6C
- Successful demonstration of installation procedure
- Tool functioned as designed, 9F temp rise measured at surface
- Well developed pump issues after 3 weeks
- Friction coupling deemed incapable of working for a wide range of well operating parameters



Field Test , Electra Field

Heater installation into the tubing (Waggoner A NCT-3 #798).

Field Test , Electra Field

Lead screw and spool installation into rod string

(Waggoner A NCT-3 #798).

Field Test , Electra Field

Surface temperature monitoring

(Waggoner A NCT-3 #798).

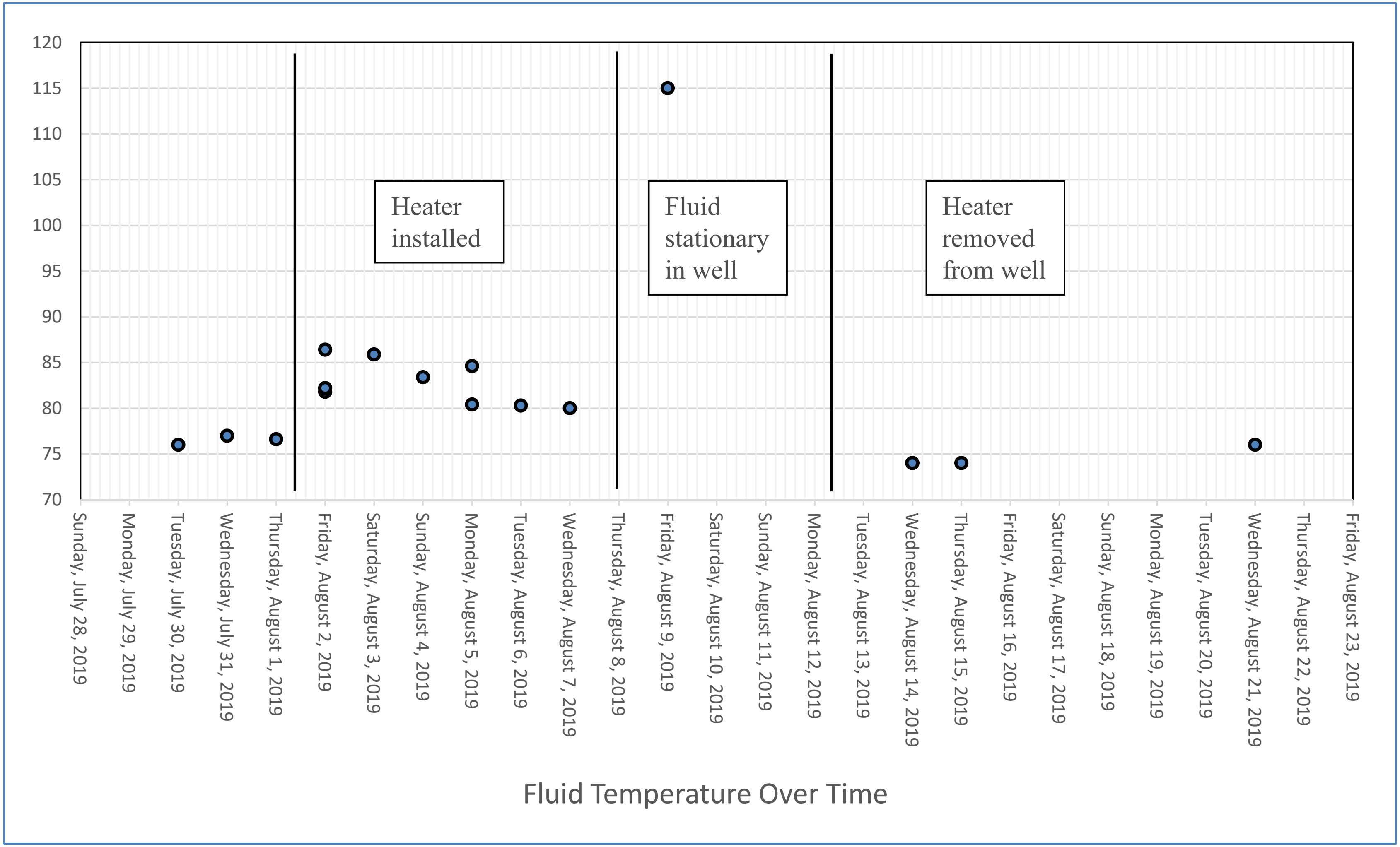
Field Test , Electra Field

Heater spool immediately after removing from well showing debris possibly caused by removal process (Waggoner A NCT-3 #798).

Field Test , Electra Field (Aug. 2019)

Surface Temperature Results

(Waggoner A NCT-3 #798).

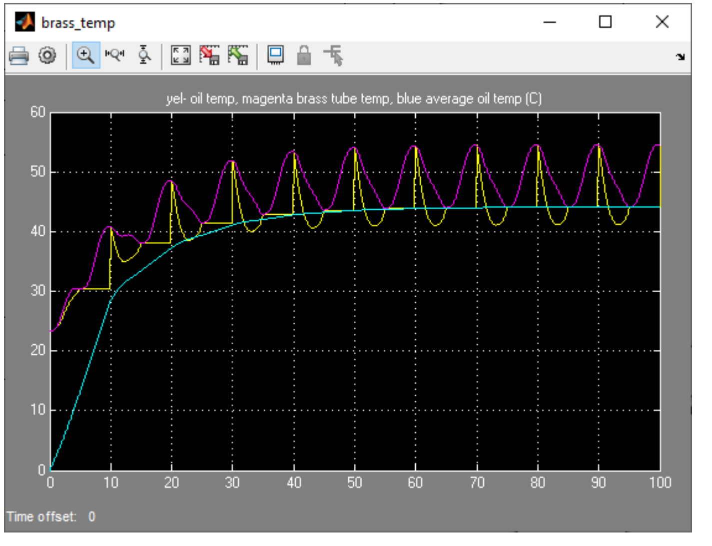


Summary of Field Test

- The installation and removal of the heater was successful and quite straightforward.
- The heating achieved was exactly what we expected.
- The evidence of toque on the surface was direct evidence of the heater being engaged.
- A very large temperature increase was recorded when the well stopped flowing (as expected).
- The tool after 3 weeks of operation was in good shape. No evidence of visible wear and tear.

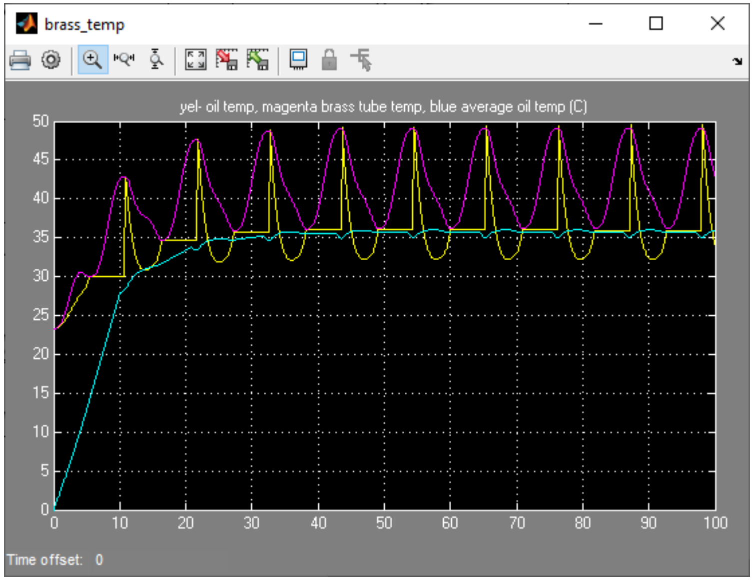
Field Test #2—Karnes City, Tx
RW Dirks (Apr. 2021)

- Self-starter design
- 2-3/8” tubing, 1-7/8” X 4 lead screw X 22’ long
- Tool depth—3819 ft
- 144” max stroke on jack
- 6 strokes per minute
- Assumed: 80% oil and 20% water
- 51.2 bbl/day oil, 12.8 bbl/day water estimated
- Predicted:
  - Ave horsepower required: 4.4hp
  - Sucker rod force +/- 1250 lb
  - Sucker rod torque +/- 45 ft-lbs
  - Ave temperature oil temp rise 20C
- Installation depth (3819’), well depth (11,000), good stress test for heater components
- Effectiveness of tool not evident, surface temperature data inconclusive
- Well produced for 13 months (rod parted, not near tool)
- Tool had little to no wear and full of paraffin, not clear if tool was properly engaged

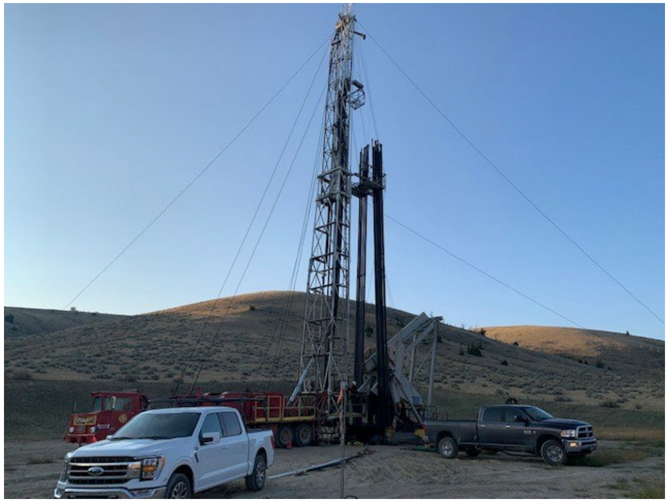


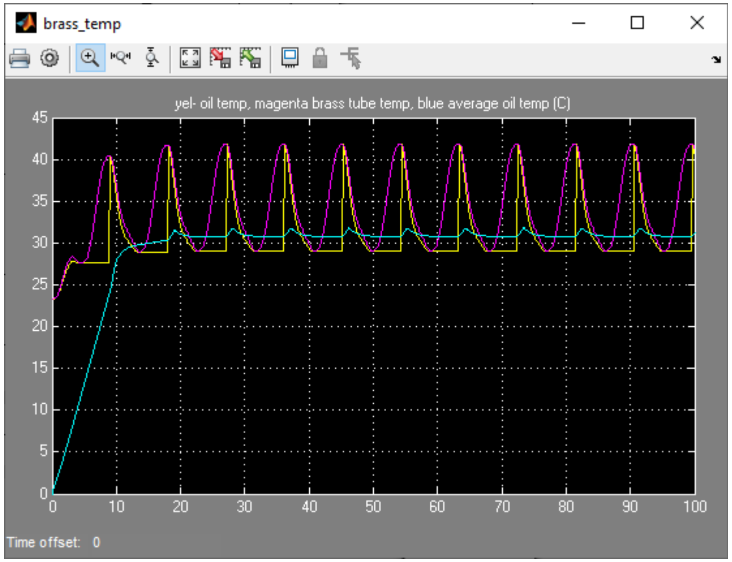
Field Test #3—Robert Lee, TX NEIAB (Aug. 2021)

- Snap-in coupling
- 2-3/8” tubing, 1” X 2 lead screw X 14’ long
- Tool depth—1944 ft
- 84” max stroke on jack
- 5.5 strokes per minute
- 83% oil and 17% water
- 10 bbl/day oil, 2 bbl/day water estimated
- Predicted:
  - Ave horsepower required: 5hp
  - Sucker rod force +/- 2600 lb
  - Sucker rod torque +/- 45 ft-lbs
  - Ave oil temperature rise: 10C
- Well productivity reported to be excellent 13 months after installation. Previously required hot-oiling every 2 - 4 months.
- Still operating after 15 months.



Field Test #4—Meeteetse, WY
Merit Energy (Sept. 2021)



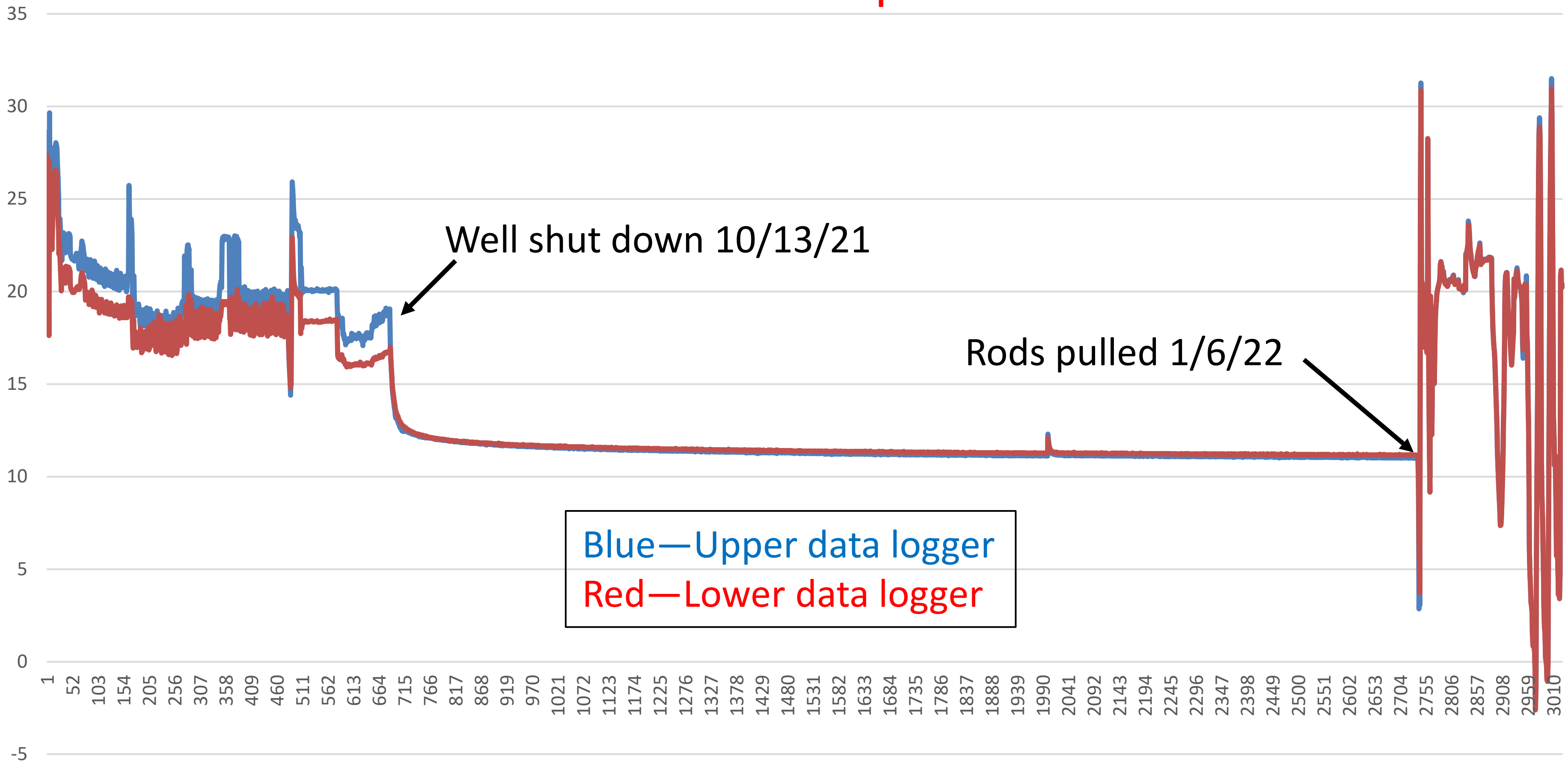


- Snap-in coupling
- 2-7/8" tubing, 1-7/16" X 3 lead screw X 22' long
- Tool Depth: 505'
- 121" max stroke on jack
- 6.62 strokes per minute
- 17.5% oil and 82.5% water
- 18 bbl/day oil, 85 bbl/day water (estimated)
- Predicted:
  - Average horsepower required: 6hp
  - Sucker rod force +/- 2000 lb
  - Sucker rod torque +/- 50 ft-lbs
  - Ave oil temperature rise 10C
- Tool heated fluids in well by about 14F (see charts)
- Tool locked up after 5 weeks possibly due to compromised bearing seals and/or 30% cycle time.

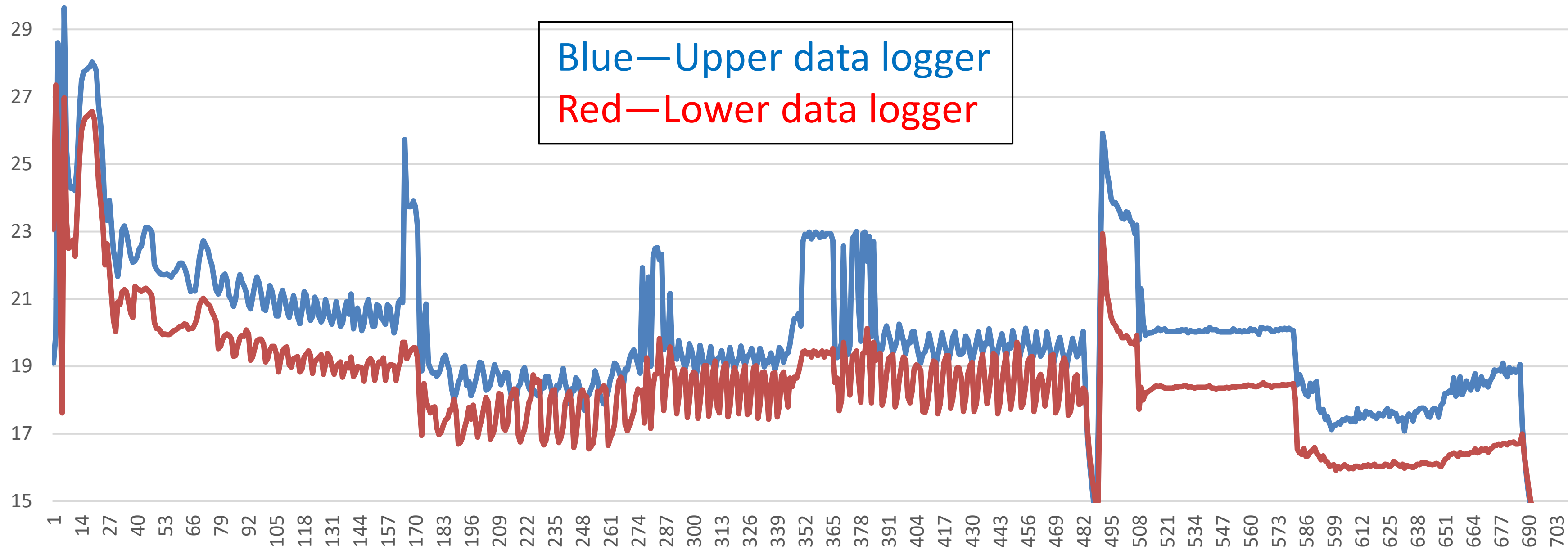
Merit Well Temp Data 9/14/21 to 1/18/22

Temperature Data Loggers Located in Lead-Screw Couplings

Record interval: 1 per hour



Merit Well Temp Data 9/14/21 thru 10/13/21

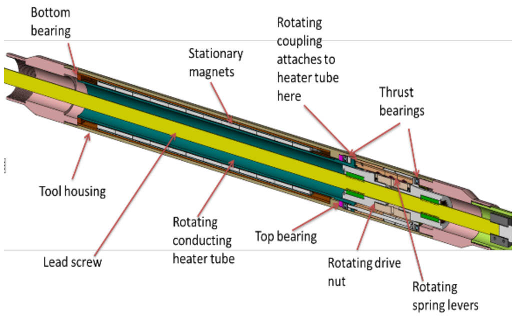


- Tool heated the fluids in the well by about 8C or 14.4F.
- The rod string was being cycled (turned on and off at periodic intervals) to optimize the fluid loading in the pump.
- The cycle time was about 30% (which means that the well was being pumped only about 30% of the time).

Field Test Summaries

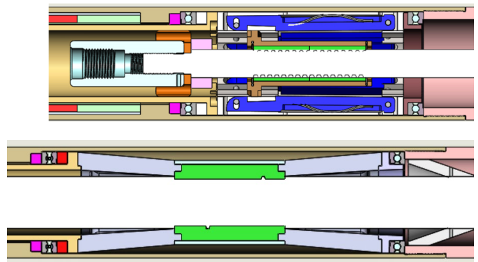
- Field Test #1 (friction coupling design), Electra, TX, Layline Energy (Aug. 2019)
  - Successful demonstration installation procedure
  - Tool functioned as designed, 9F temp rise measured at surface (tool was installed at 66’)
  - Well developed pump issues after 3 weeks. Our tool was in great shape.
  - Friction coupling deemed incapable of working for a wide range of well operating parameters
- Field Test #2 (self-starter design), Karnes City, TX, RW Dirks (Apr. 2021)
  - Installation depth (5000’), well depth (11,000), good stress test for heater components
  - Effectiveness of tool not evident, surface temperature data inconclusive
  - Well was productive for 13 months (rod parted, not near tool)
  - Tool had little to no wear and full of paraffin, not clear if tool was properly engaged
- Field Test #3 (snap-in coupling design), Robert Lee, TX, NEIB (Aug. 2021)
  - 2-3/8” tubing, 1” X 2 lead screw X 14’ long
  - Well productivity reported to be excellent 13 months after installation
  - Still operating
- Field Test #4 (snap-in coupling design), Meeteetse, WY, Merit Energy (Sept. 2021)
  - 2-7/8” tubing, 1-7/16” X 3 lead screw X 22’ long
  - Tool heated fluids in well by about 14F
  - Tool locked up after 5 weeks possibly due to compromised bearing seals and/or 30% cyclic operation

Phase I



- Full-scale prototype tool built & tested in a simulated wellbore
- Tool simulation & design tools built.

Phase II



- Full-scale prototype tools designed, built, installed & tested in 4 commercial oil wells.
- Lessons learned, design enhancements incorporated
- 7 commercial tools designed & built for 2 3/8" & 2 7/8" tubing.

Phase IIB

Path to Commercialization (Tasks)

1. Improve tool designs—Optimize costs, Reduce risk, accelerate deployment, simplify tool installation.
2. Develop design tools for sales engineers and customers
3. Develop manufacturing & maintenance supply chain
4. Build and deploy additional tools in the field
5. Prepare Case Studies, marketing materials--Refine market opportunities
6. Build network of sales/service reps
7. Make continuous improvements to tool

Phase IIB: Tasks

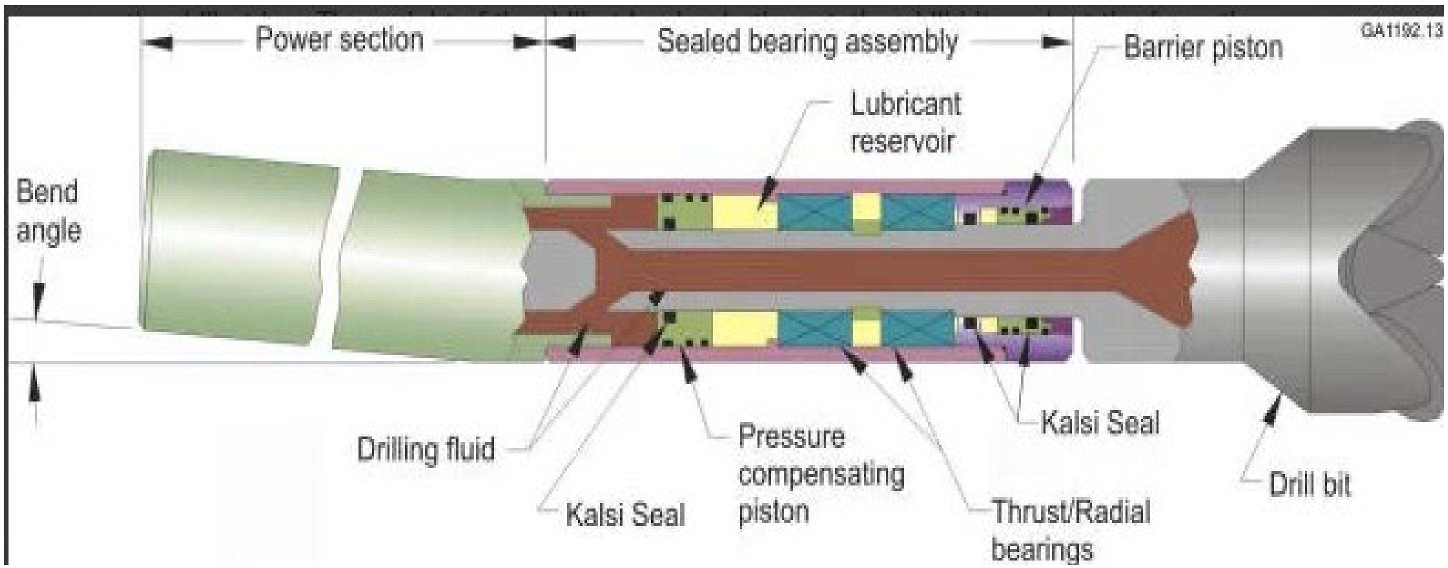
- **Task 1: Simplify the Tool Design to Reduce the Cost of Construction and Assembly**
- **Task 2: Develop Design Tools for our Sales Engineers and Customers**
- **Task 3: Develop a supply chain for tool manufacture and maintenance**
- **Task 4: Build and deploy 6 additional tools and document these case studies for clients.**
- **Task 5: Prepare Case Studies, marketing materials and further refine the market opportunity**
- **Task 6: Build a Network of area sales/service representatives to market and service the tool.**
- **Task 7: Make Continuous Improvements to the Tool Design.**
- **Task 8: Final Report**

Task 1: Generation III Design Enhancements

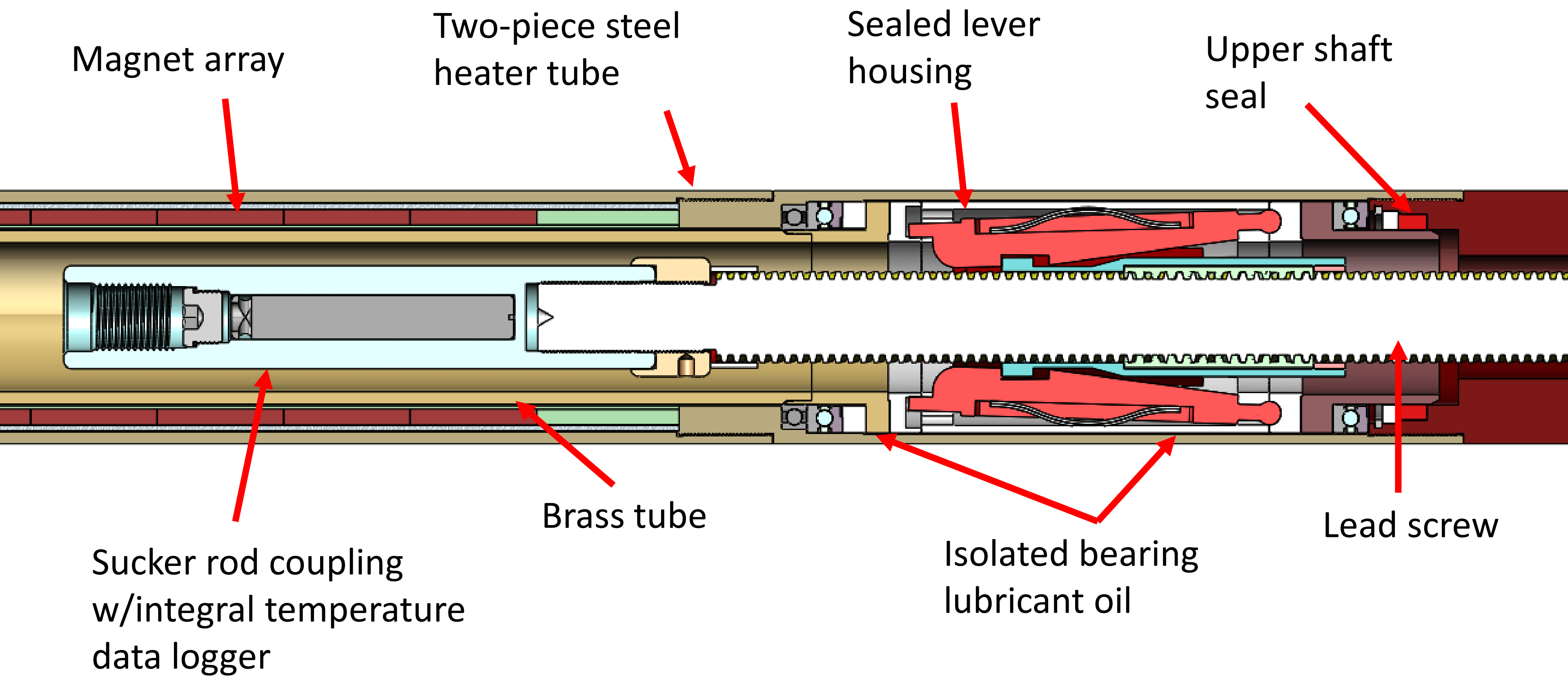
- Improved isolation of bearings from dirty well oil-created-lubrication reservoir
  - Eliminated radial penetrations in snap-in coupling
  - Added seals at ends of tool
- Manufacturing cost saving changes
  - Modified lever pivot to eliminate dowels and simplify lever housing machining
  - Added joint in heater tube to eliminate need for specialized boring tools
  - Moved lower radial bearing into cross-over to eliminate machining steps
  - Redesigned sucker rod coupling to accommodate less expensive (and larger memory capacity) temperature data logger

Task 1: Simplify the Tool Design to Reduce the Cost of Construction and Assembly

- Use a Kalsi Seal similar to those used in mud motors to protect the bearings in the heater tool.
- The bridal of the pump jack has twisted on occasion indicating that free rotation of the tool is obstructed. Increase the area of flow passages to address this issue.



Generation III Design
(upper tool)



Task 2: Develop Design Tools for our Sales Engineers and Customers

- Develop a user accessible spreadsheet that clearly identifies the inputs for a given well and then predicts expected performance.
  - A thermal model for the well to estimate the heater capacity (in KW and HP) needed for the well and the expected temperature profile along the well, before and after heater installation.
  - A electro-mechanical analysis of the magnet array to compute the loads generated on the rods and lead screw during the operation of the pump.
  - A mechanical analysis of the loads in rod string to ensure that the lead screw is installed in a location that does not subject any part of the rod string to compression.

Task 3: Develop a Supply Chain for Tool Manufacture and Maintenance

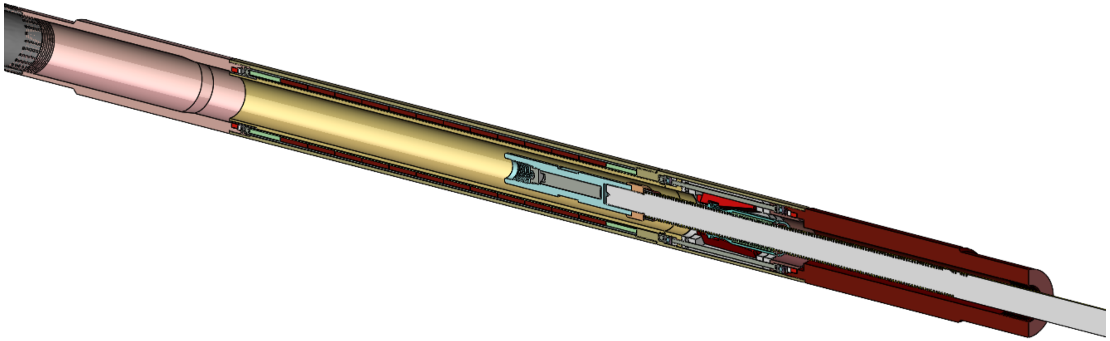
- Magnet cartridges: Magnetic Hold of Hendersonville, TN.
- Lead screw and nuts: Roton Products of St. Louis, Mo.
- Cross-overs and three-inch tubing extensions: Downhole Threading Services of Crosby, TX.
- Snap-in couplers: Diversified Machining of Bertram, TX.
- Magnet cartridge assembly and the overall tool assembly: UT-CEM and Austin Geotech.
- Identify commercial contractor and transfer technology during the assembly of the next tool batch.

Task 4: Build and Deploy 6 tools and Document These Case Studies for Clients.

- Request bids for tool parts and look for options for better suppliers.
  - Cost of materials has shot up in the past 6 months.
  - Lead times are twice as long.
- Identify commercial contractor to manage assembly and maintenance of the tools.

Task 4:
Building Paraffin Heater (Generation III Tools)

- Incorporates lessons learned from field deployments and manufacturing experiences
- Four “snap-in” tool configurations available
  - 2 tubing sizes: 2-3/8” and 2-7/8” tubing
  - 2 lead screw sizes: 1 X 2 (14’ length) or 1-7/16” X 3 (22’ length)
- Majority of components are interchangeable all tool configurations
- Received bids last week for all parts. Tool costs are below Gen. II tools.
- Expect to have all parts built for 6 tools by January 2023.



Task 5: Conduct Case Studies, Prepare Marketing Materials and Refine Market Opportunity

- Prepare an installation notebook for each well.
- Simulation (expected) results
- The installation procedure has been documented for operators
- Downhole temperature recorders are now incorporated into the tool to ensure we have accurate downhole data on tool operation.
- Next well (near Bakersfield) will have fiber optic data to continuously record temperature in the entire well (not just at one location).
- Merit Energy has 2 wells we can deploy Gen III tools in.

Task 6: Build a Network of area sales/service representatives to market and service the tool.

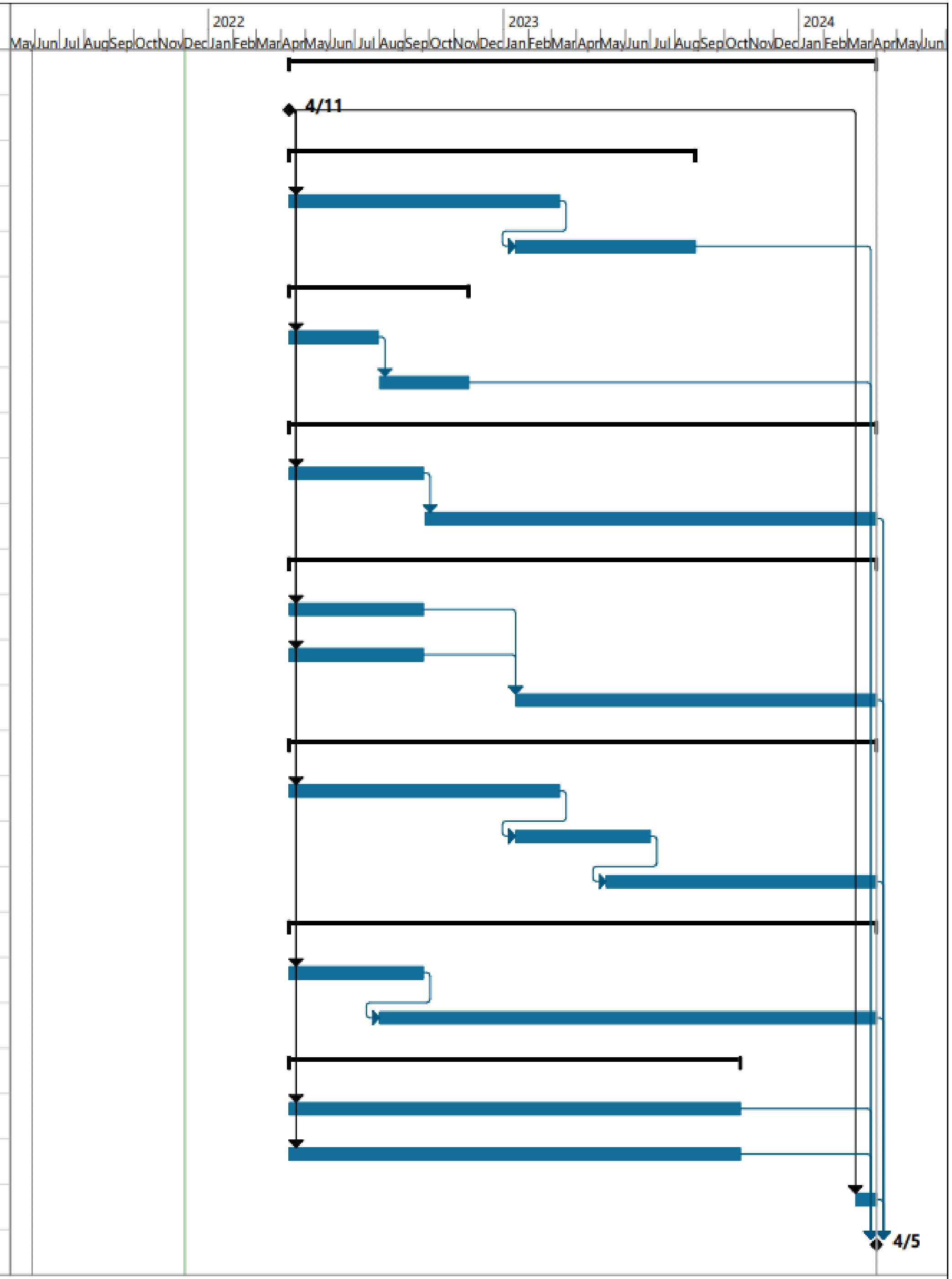
- To install the tool in many wells every month we will need to build a network of sales and service providers that will be well trained in the installation and servicing of the tool.
- Agreements for sales and distribution rights in specific geographic regions will be negotiated with companies to ensure that a suitable level of sales can be maintained.
  - Potential partner: Harbison Fischer a subsidiary of Champion X has helped us procure lead screw material in the past.
- It is anticipated that most simple tool repairs will be conducted by the sales engineers that install the heater in the well. They will be assisted by technicians from AGS.
- More complex repairs, such as replacement of parts or rebuilding the magnet array will be handled in a central repair facility in Austin.
- Prepare sample agreements for distributors who have extensive experience in the sale and maintenance of downhole tools.

Task 7: Make Continuous Improvements to the Tool Design

Some of the design features that are being given particular attention are listed below:

- API certification of components
- Longer, stronger, cheaper lead screws (already underway)
- Lead screw coupling redesign (done)
- Open-up heater fluid flow area to reduce heater tool pressure drop (done)
- Heat oil only on down stroke--utilize sucker rod weight, freewheel on upstroke (design complete, if needed)

ID	Task Name	Duration
1	**DOE Paraffin Heater Program Phase IIB**	**520 days**
2	Funding Authorization	0 days
3	**Task 1--Improve tool designs**	**360 days**
4	Simplify tool design to minimize production costs	12 mons
5	Modify tool production drawings	8 mons
6	**Task 2--Develop design tools**	**160 days**
7	Simplify Thermal, EM & Mechanical models	4 mons
8	Integrate simplified models	4 mons
9	**Task 3--Develop supply chain**	**520 days**
10	Identify qualified manufacturers	6 mons
11	Develop pathway for commercializing mfg & assm	20 mons
12	**Task 4--Build & deploy additional tools**	**520 days**
13	Manufacture & deploy 6ea 2-3/8" tools	6 mons
14	Manufacture & deploy 6ea 2-7/8' tools	6 mons
15	Manufacture & deploy 6ea tools using generated renvenue	16 mons
16	**Task 5--Prepare Case Studies**	**520 days**
17	Collect field data	12 mons
18	Compile & create data base	6 mons
19	Develop marketing tools	12 mons
20	**Task 6--Build network of sales/service reps**	**520 days**
21	Generate list of candidate tool sales/service reps	6 mons
22	Negotiate sales & distribution right agreements	22 mons
23	**Task 7--Continued tool improvements**	**400 days**
24	Evaluate tool coupling design options	20 mons
25	Evalute performance & riability design improvements	20 mons
26	**Task 8--Final Report**	1 mon
27	DOE Paraffin Heater Program Phase IIB Complete	0 days



Thank You

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