An Optimization Study of EUV Sources Driven by CO_2 and Thulium Lasers

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HYDRA simulations can efficiently explore the utility of different lasers for EUVL sources

- Current laser driven EUVL sources use a CO_2 laser to heat a tin target.
- Other lasers can also drive tin into the temperature and density range where strong 13.5 nm emission occurs.
- Building a new laser and experimentally optimizing its performance is a slow and expensive process.
- Computer simulations can be used to quickly find promising laser designs and reject designs that are unlikely to be efficient at producing 13.5 nm light.
- This study uses HYDRA to simulate 13.5 nm EUV sources. HYDRA previously simulated CO_2 laser driven sources under a cooperative R&D agreement with Cymer/ASML.
- HYDRA can also simulate EUV source wavelengths shorter than 13.5 nm (Blue X).

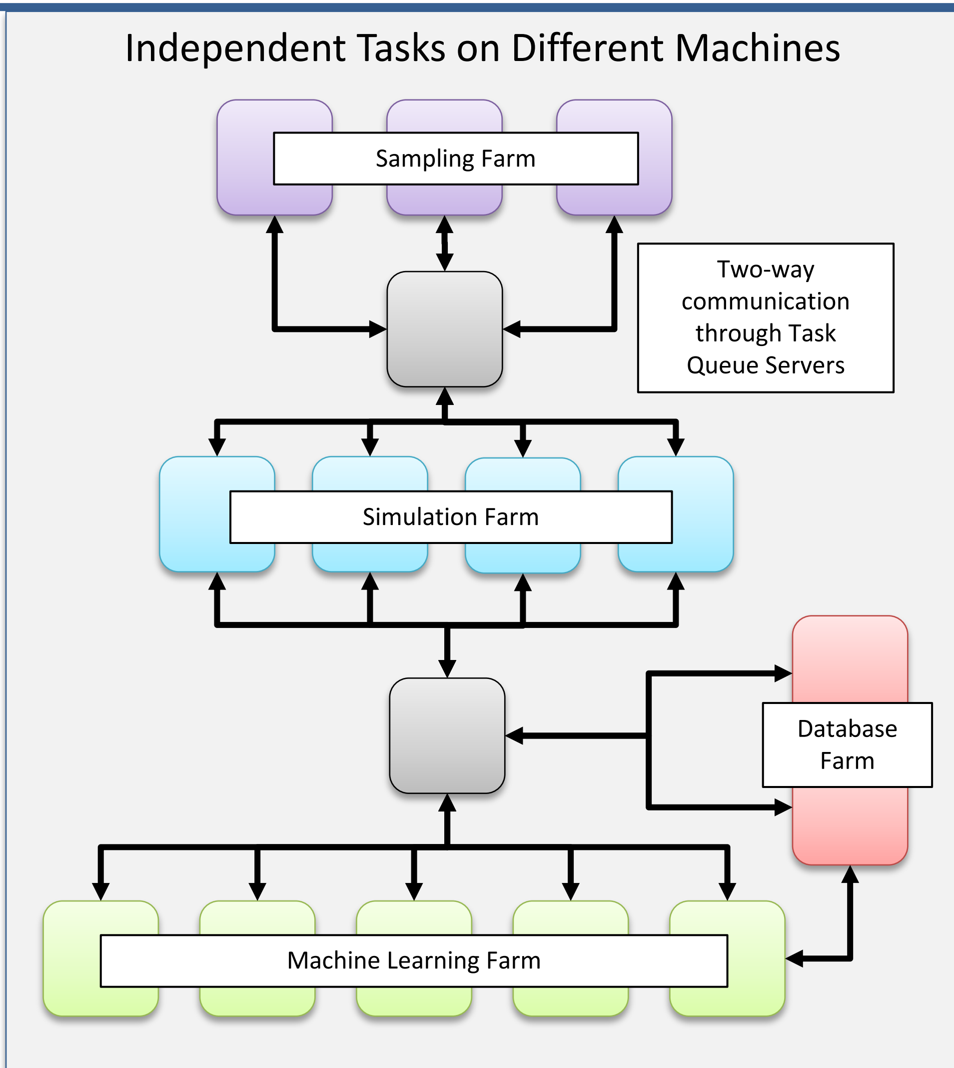
Ensembles of simulations are used to understand how a target performs

- The performance depends on the characteristics of the laser pulse and the target.
- Running an ensemble of simulations that span a range in a multi-dimensional parameter space can identify the parameters that optimize EUV performance.
- The number of simulations required to investigate a multi-dimensional parameter space is large.
- Running simulations manually becomes impractical for more than ~100 simulations.
- Merlin is a workflow manager under development at LLNL.
- Merlin automates the running of ensemble simulations and allows a scientist to focus on understanding the physics of EUV generation.

Merlin enables running large ensembles without massive amounts of bookkeeping

- The user supplies a parameterized "template" HYDRA input deck.
- Merlin generates sample parameter sets within a user specified parameter range, creates an input deck for each parameter set, and runs the HYDRA simulations.
- Merlin invokes post-processing code for each simulation to generate an EUV spectrum.
- Merlin currently creates a surrogate model that fits the conversion efficiency (CE) after *all* HYDRA runs are complete.
- Merlin makes it easy for users to add custom steps to their workflow.
- In the future, Merlin will build surrogate models as the simulation runs and use the model to adaptively sample interesting parameter regions which have high uncertainty.

Merlin splits the work between multiple components that communicate via task queues



- A key goal of Merlin is to scale to very large numbers of simultaneous simulations.
- Sampling, simulations, post-processing, and machine learning all run simultaneous tasks on many servers and communicate via the task queue.
- Merlin has run an ensemble with 100 million simple ICF simulations.
- Merlin routinely runs ensembles with 10,000 HYDRA simulations.
- Merlin is ready to run the largest EUVL ensemble we are likely to need.

This study uses *simple* tin targets to demonstrate the capabilities of HYDRA and Merlin

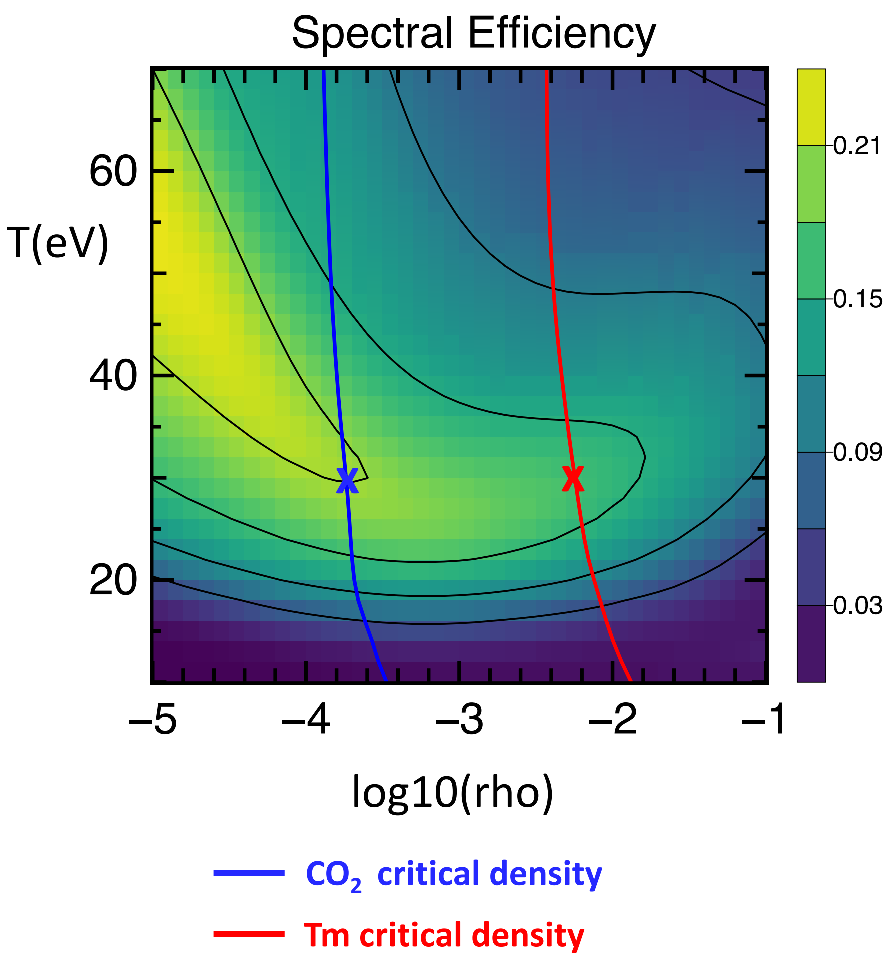
- The target is a cylinder of uniform density tin vapor.
- The laser heats one end of the cylinder.
- The simulations ignore variations transverse to the laser direction. The resulting 1D simulations run in a few hours on one node of a computational cluster.
- The HYDRA simulations include hydrodynamics, laser ray tracing, radiation transport, heat conduction, and non-LTE opacities and emissivities – the processes shown to be important in prior work[1].
- Our talk in November 2018 was based on ~25 simulations run by hand. A 1000 simulation ensemble can now be completed in a day on 32 nodes.

[1]Purvis et al. In Proceedings Volume 9776, Extreme Ultraviolet (EUV) Lithography VII. SPIE, Mar. 2016.

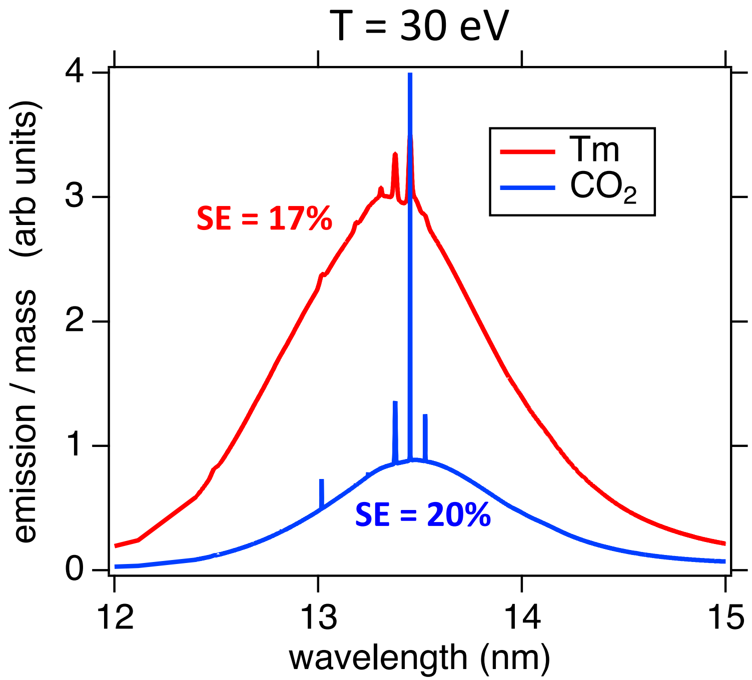
Ensemble simulations have investigated the CE from tin targets heated by a thulium laser

- The thulium laser design (discussed earlier by Siders) has several potential advantages
  - Higher average power than current CO_2 lasers
  - Less pulse-to-pulse variation than CO_2 lasers
  - Excellent pulse shaping capability
  - Very good wall plug efficiency
- The thulium laser has a wavelength of 1.88 μm, so the critical density is ~30 times greater than for a CO_2 laser.
- The fraction of tin emission in the 2% bandpass about 13.5 nm is higher at low densities, all else being equal.
- Can a thulium laser deliver higher EUV source brightness than a CO2 laser?

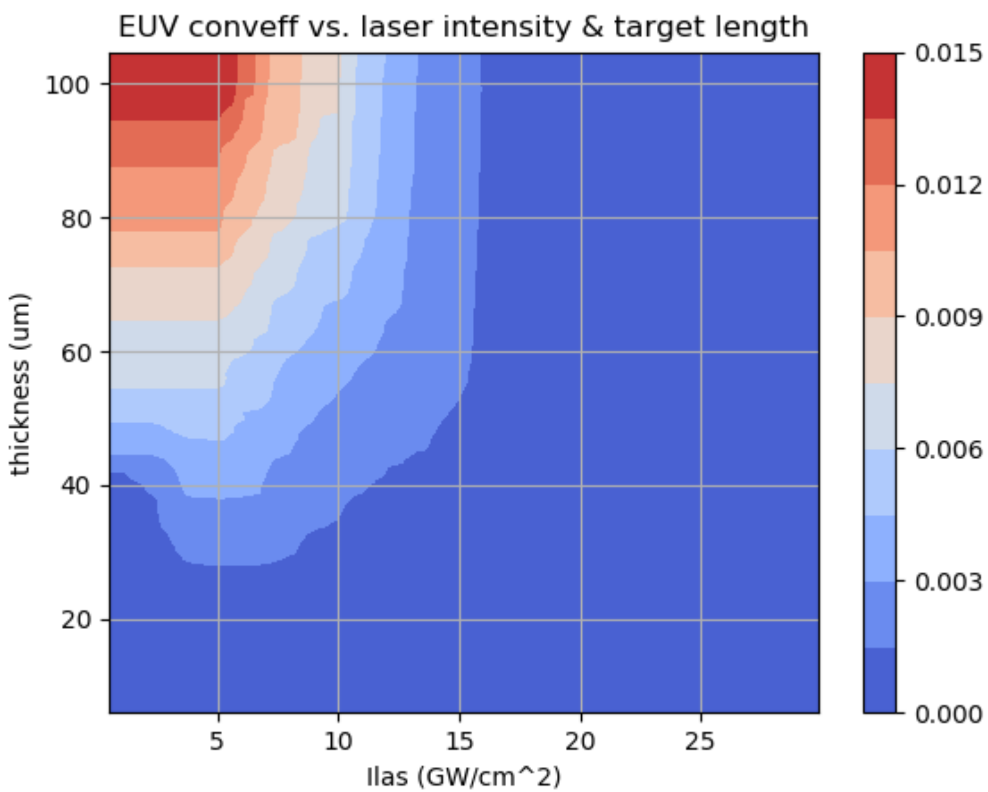
Performance at different laser wavelengths involves tradeoffs in the underlying physics



- The fraction of tin emission in the 2% bandpass about 13.5 nm is greatest at low densities.
- Emission per unit mass drops at low densities.
- Low densities require very long (>100 ns) timescales.

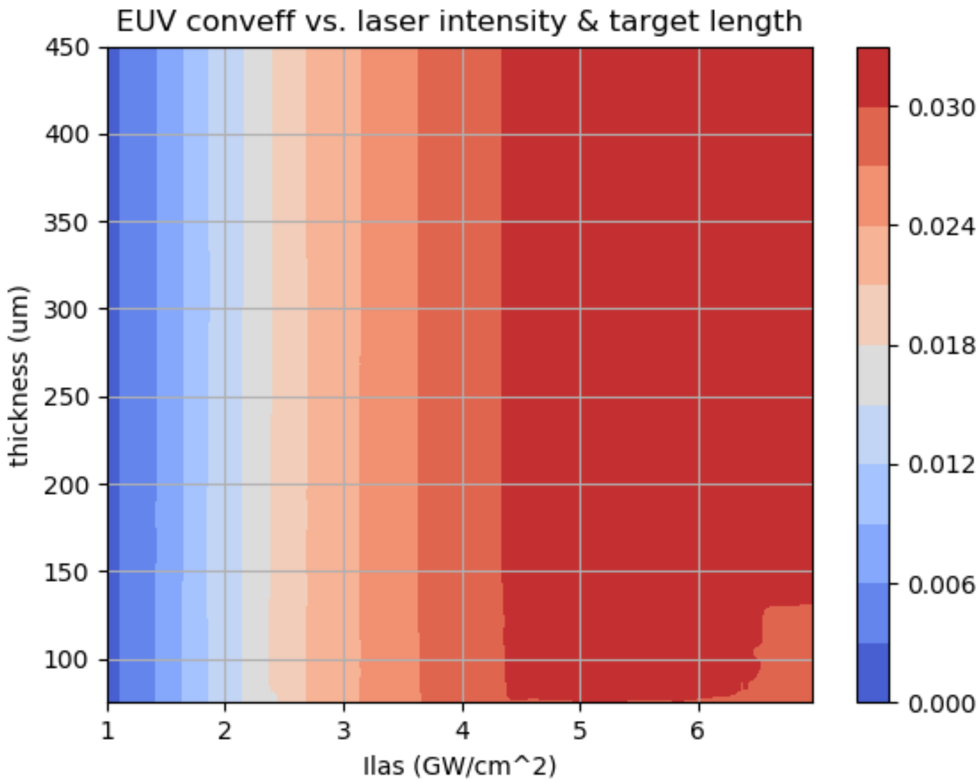


An initial thulium ensemble was run with a guess of a suitable range for target thickness and laser intensity



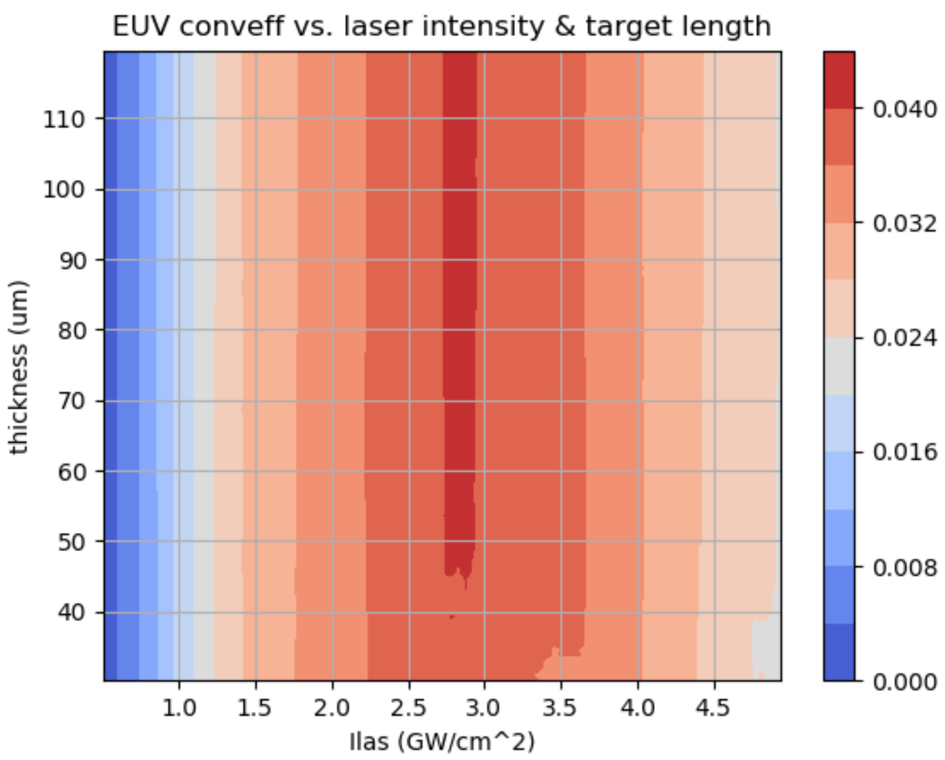
- The highest CE in this ensemble was 1.5%.
- The laser intensity varied between and 5 and 20 GW/cm^2.
- The target thickness varied between and 45 and 105 μm.
- The density was 0.01 g/cm3.
- 1555 simulations were run.
- *The next ensemble needs to have lower laser intensity and greater target thickness*.

Later ensembles have higher conversion efficiencies as they move closer to optimum conditions



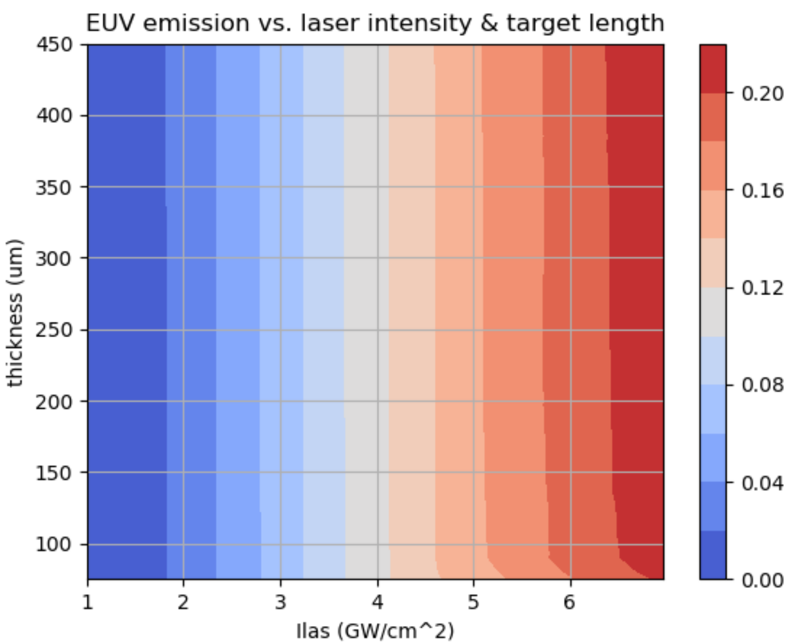
- The highest CE in this ensemble was 3.3%.
- The laser intensity varied between and 1 and 7 GW/cm^2.
- The target thickness varied between and 75 and 450 μm.
- The density was 0.04 g/cm3.
- 365 simulations were run.

The CO2 ensemble has a somewhat higher maximum CE than the thulium ensemble

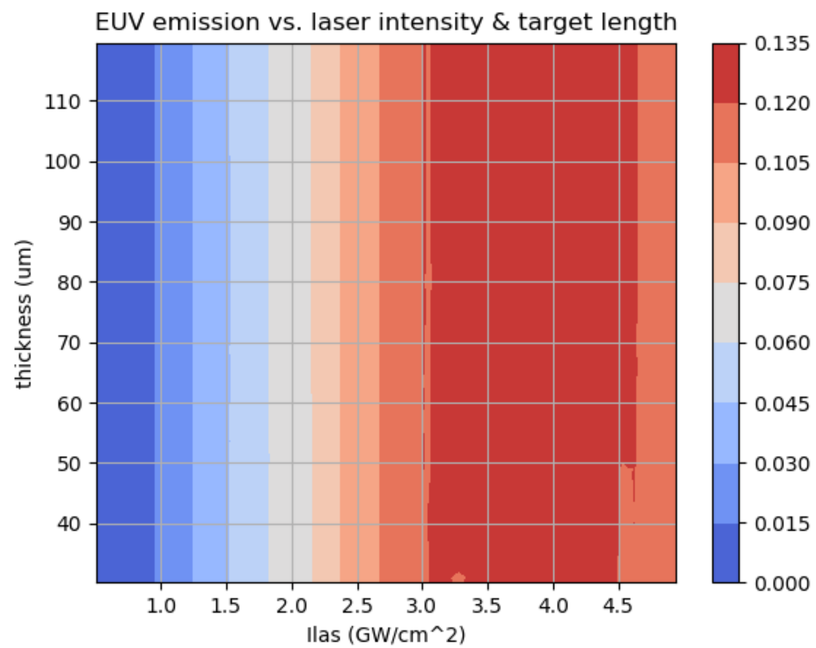


- The highest CE in this ensemble was 4.4%.
- The laser intensity varied between and 0.5 and 5 GW/cm^2.
- The target thickness varied between and 30 and 120 μm.
- 256 simulations were run.

The Tm ensemble has a somewhat higher EUV exposure than the CO_2 ensemble



Tm



CO2

- A minimum "dose" of EUV is required to expose a wafer. The best Tm run has a ~50% higher EUV exposure than the best CO_2 run.
- The total EUV exposure from Tm will increase at laser intensities above 6 GW/cm^2. It will be easy to design a Tm laser to reach the desired intensity.

HYDRA Ensembles indicate that the thulium laser deserves further study

- The HYDRA+Merlin ensemble simulation capability is ready to use in evaluating laser driven EUVL sources. Studies of how EUV emission varies across parameter ranges can be run quickly rather than slowly running simulations sequentially by hand.
- The highest CE seen in ensembles run so far is 3.3% for thulium and 4.4% for CO_2. Further optimization is in progress.
- CO_2 driven experiments have delivered a ~7% CE. The simulated and experimental CEs are close enough to indicate that tin vapor targets are relevant.
- The best thulium run has a higher total EUV exposure than the best CO2 run.
- The 1D tin vapor target is very simplified, but gives a good idea of the optimal laser intensity and target thickness.
- Once an interesting operating point has been identified by 1D runs, 2D ensemble simulations can be run to produce a more accurate answer.

A vision for future EUVL source development

- A campaign to develop a new EUVL source starts with candidate lasers and targets.
- Simulations quickly optimize the performance of the candidates. Candidates are adjusted based on simulation results. The process requires no hardware.
- Test facilities are built for the winning candidate(s).
- Simulations are used to help understand departures from the predicted performance and steer experiments towards better performance.
- A production source is designed and built.

This process would be faster and less expensive than a purely experimental approach.