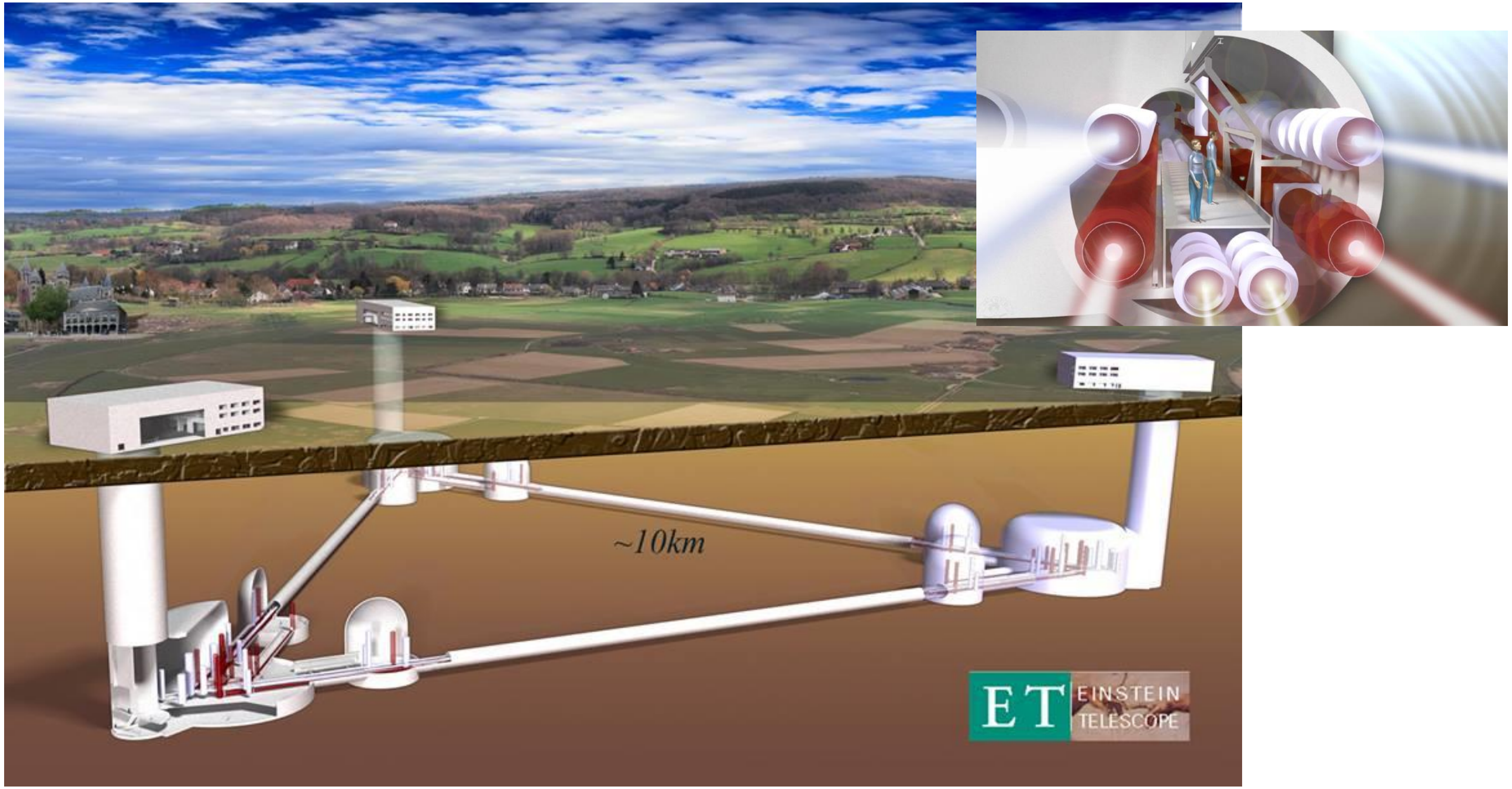
September 30-October 2, 2025

Cosmic Explorer - Einstein Telescope Beamtube Workshop III

LIGO Hanford Observatory, Richland, Washington, USA

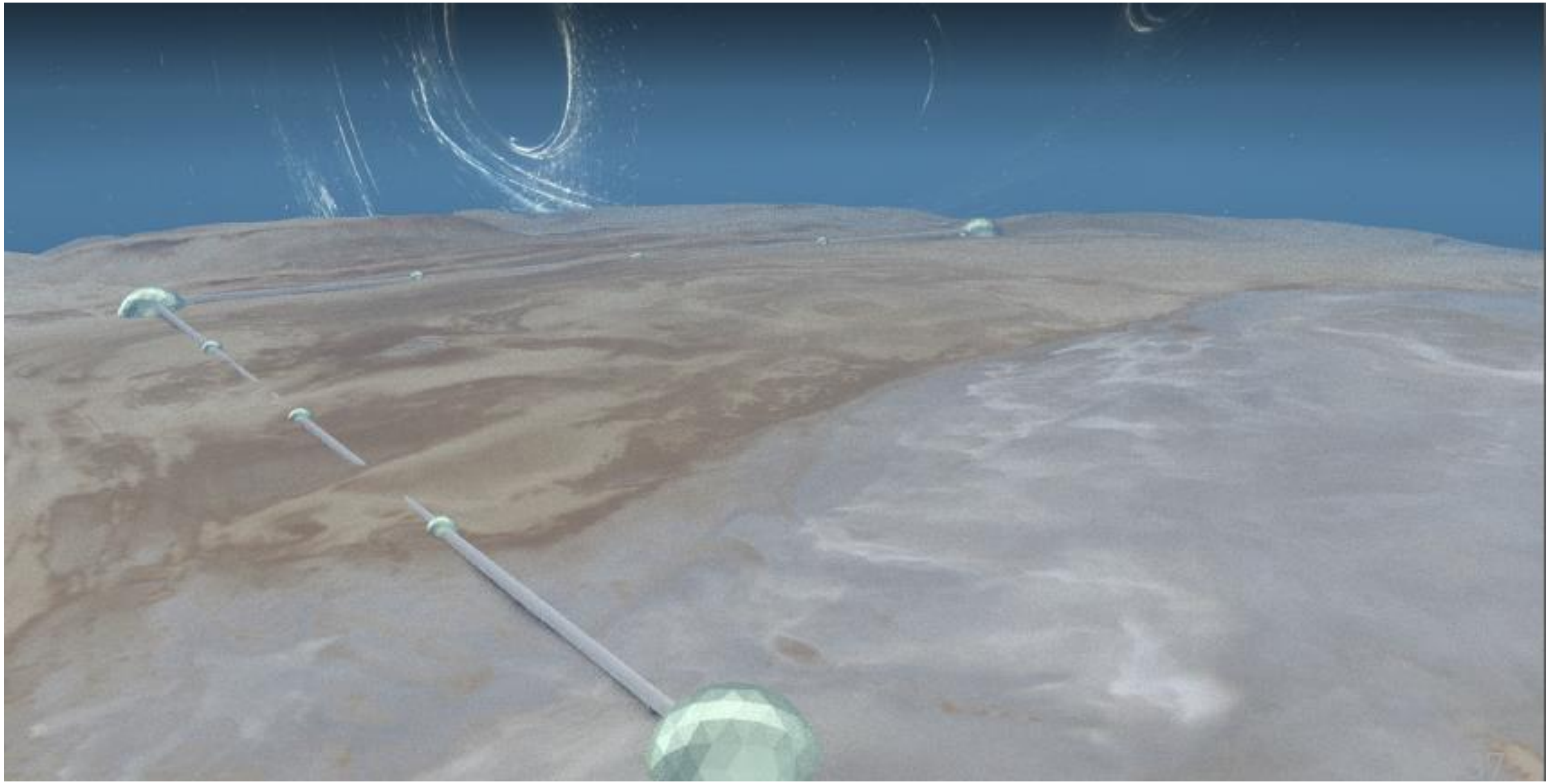
Einstein Telescope 10 km x 10km x 10km

www.et-gw.eu



Cosmic Explorer: 40 km x 40 km

https://cosmicexplorer.org



Continuity between the GWD Beam Tube Workshops

BTW 1: LIGO Livingston Observatory: Jan. 28-31, 2019

BTW 2: CERN: March 27-29, 2023

BTW 3: LIGO Hanford Observatory: Sept. 30-Oct. 2, 2025

Initiated teleconferences with: "**CE Vacuum Studies Group**"

on July 7, 2021

Initiated bimonthly teleconferences with **CE Group and CERN VSC**

on Oct. 22,2011

24 bi-monthly calls since then with ~40 participants

Opening Session from the CERN 2023 Workshop

- Inspiring talk by **Rai Weiss** (on Zoom) on the new physics that CE and ET could uncover
- **Mike Zucker** reviewing the physics that drove the ambitious vacuum requirements for GWD beam tubes
- **Fred Dylla** reviewed Beam Tube Workshop 1 held in LLO in January of 2019

Preliminary conclusions from BTW1:

- LIGO's and Virgo's vacuum achievements meet CE/ET requirements but straightforward extrapolation of LIGO beam tubes to 80km would exceed $0.5B
- Hence the driver for less costly BT designs (perhaps with mild steels)
- In addition to desired decreased costs for bakeout and operations.

Summary of the GWD Vacuum Workshop at CERN
March 27-29,2023

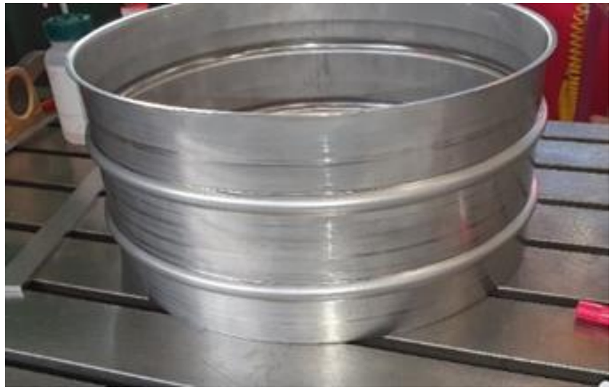
Activities at CERN and partner European Labs for the Einstein Telescope (ET)

- The ET Prototype Vacuum Tube project at CERN VSC was just beginning
- Initially 3-years; expanded to year 5
- Three prototype vessels: 304L, mild steel (S355) and ferritic steel (430)
- Supporting outgassing measurements on mild steels, ferritic steels and a silicon compound coated 304SS
- Supporting modelling of outgassing behavior

ET Pre-Prototype Test Chambers

- 3 materials for comparison Tests:

AISI 304L, S315 mild steel, AISI 430 ferritic



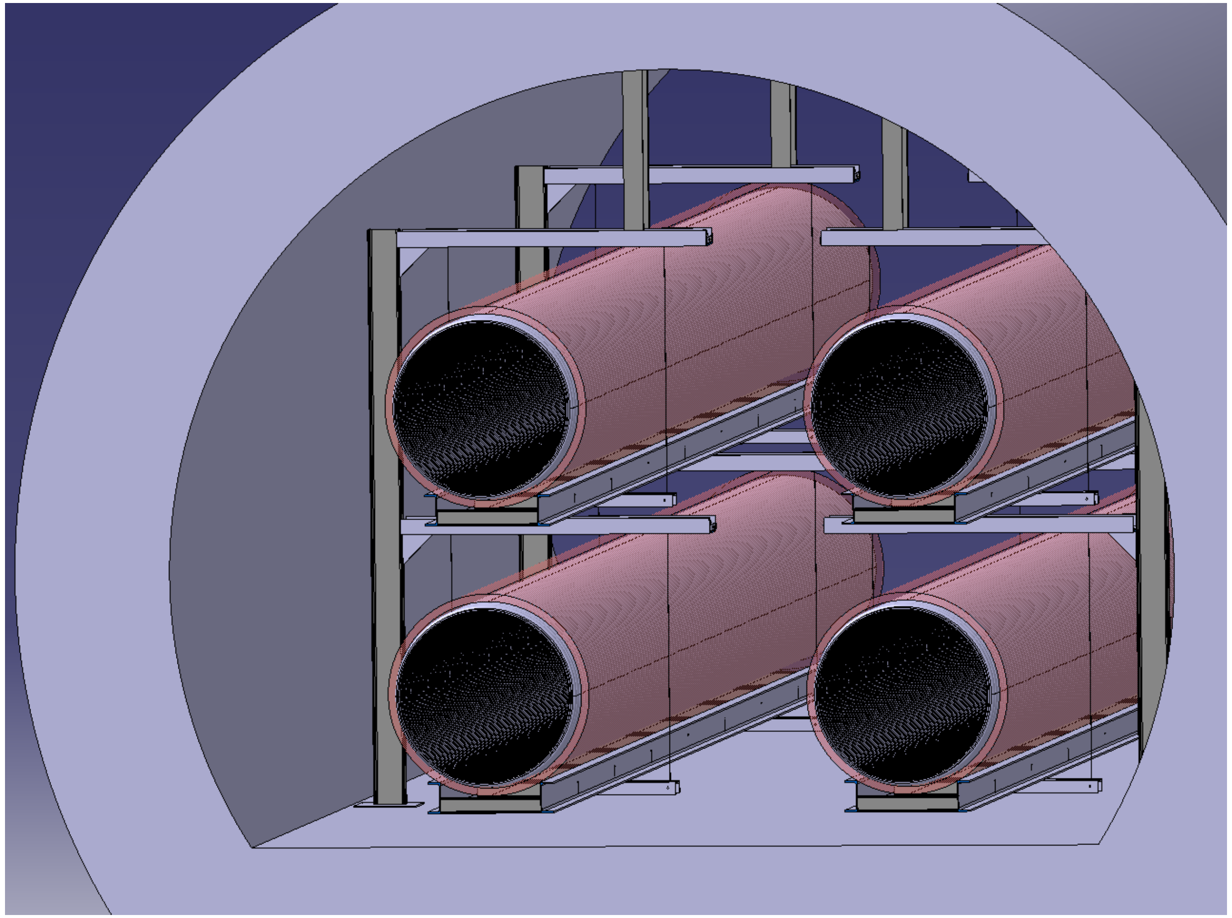
304L prototype

S315MC

304L + VF

Photos curtesy of Leonel Ferreira

Preliminary designs for ET chamber suspension mounts in tunnel-Cedric Garion



ET Design Team Reports for Detailed Design and Manufacturing Issues

- Baffle design issues-Mario Martinez-Perez
- Parametric study of the BT vacuum system- Carlo Scarcia
- Leak checking issues and preliminary cost-Paul Cruikschank
- In-tunnel manufacturing option- Marion Purrio
- Dust management –Andrea Moscatello (CERN)
- Beam tube manufacturing & installation cost model-Luigi Scibile

Remarkable CERN VSC-Pan European Collaboration

- ET Organization
- Nikhef (NL)
- INFN (IT)
- IFAE (ES)
- PIEP and University of Minho (PT)
- Aachen University (DE):
- MACBETH (NL): Dutch consortium led by VDL
- Antwerp University (BE):
- Paul Sherrer Institute and VAT (CH)
- CNRS-LAPP (FR)
- University of Padua (IT)
- CETIM (FR)

Summary of the GWD Vacuum Workshop at CERN

March 27-29,2023

Activities in the US through the Cosmic Explorer (CE) Vacuum Studies Group

- A modest NSF grant in-place since August 2023 for CE preliminary design studies and support of scientific user collaborations (c/o, Matt Evans, MIT)
- Support of ongoing outgassing measurements on mild steels, 304SS with various surface treatments and bakeout conditions and outgassing modelling
- Preliminary sourcing of mild steel vendors for production quantities (c/o, Dan Henkel)

Jim Fedchak's (NIST) Summary of the 4-Lab Collaboration on Steel Outgassing

- Very complete inter-lab (CERN, NIST, JLab, W&M) comparison of outgassing of SS304 and mild steels
- H outgassing negligible compared to SS
- H_2O outgassing similar to SS
- Some indications that a lower bakeout temperature (80-90C) could be used for lowering H_2O outgassing
- 4 lab intercomparison showed that with:

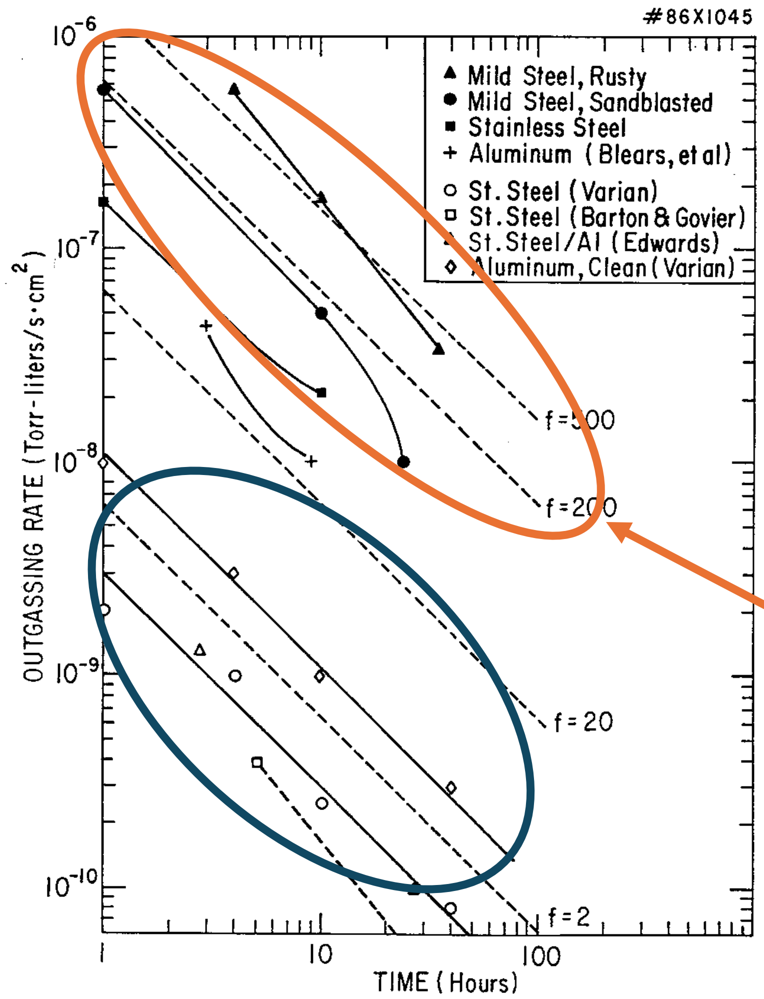
    -care of specification of the grade and surface prep

    -pre-cleaning by standard methods and

    -in-situ bakeout perhaps at less than 100C,

GWD requirements could be met by mild steels

Literature values on steel outgassing (pre-1986)



- Often quoted literature values on total outgassing from mild steels (Blears et al 1960) when plotted with with widely used and accepted curves for stainless steels done by Varian (1969) and the accelerator community Barton and Govier (1970) and Edwards (1977)

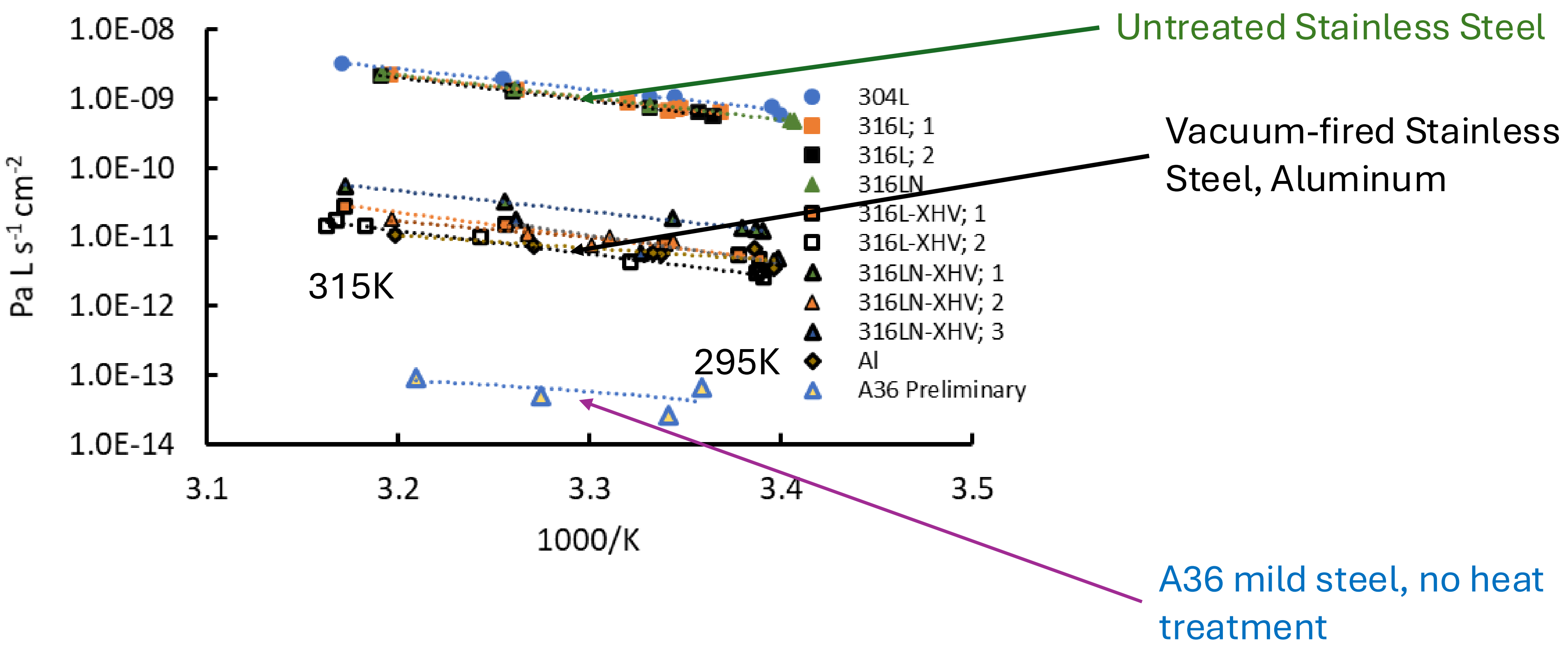
- Blears et al values appear 10^2 too large because their stainless values are in error by that amount.

- According to Park et al. (2016), vacuum degassing was developed in the 1950's, but only 10% of Japanese plants used the process by the 1970's

Blears et al

Slide courtesy of J.Fedchak, GWD Workshop 2; Dave Edwards outgassing data

NIST H_2 Outgassing data (J.Fedchak)



100 Pa = 1 mbar

Why should mild steel have low (H) outgassing?

To our knowledge **mild steel** uses the **Ruhrstahl-Heraeus** process (RH process) for **hydrogen reduction** and decarburization.

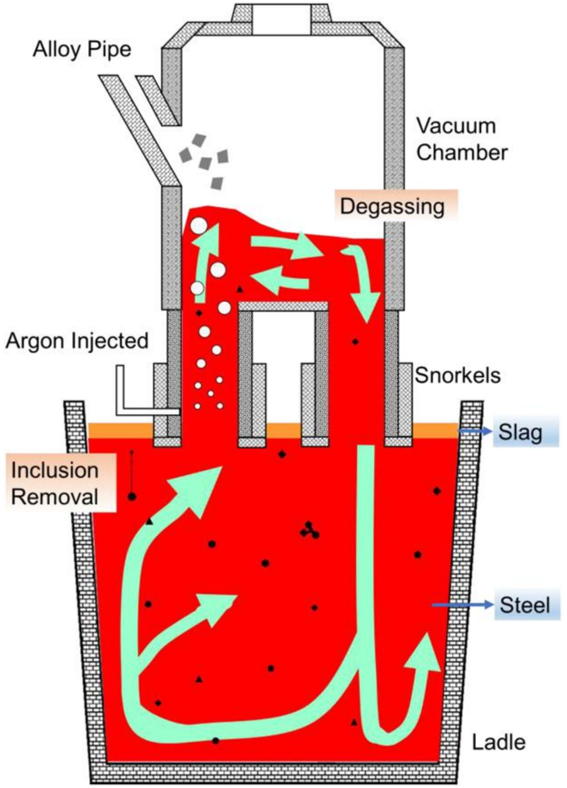
- RH is a secondary metallurgy process in which liquid steel is subjected to a vacuum treatment for decarburization and degassing H_2 and O_2

Stainless steel is typically produced from recycled steel in an electric arc furnace
- As produced, **most stainless steels contain significant dissolved H_2**

to

We sent out 4 samples for hydrogen concentration testing

Sample Identification:	Hydrogen ppm
A36 Steel # 1	0.5
A36 Steel # 2	0.5
304L Blank	3.6
316L Blank	1.9

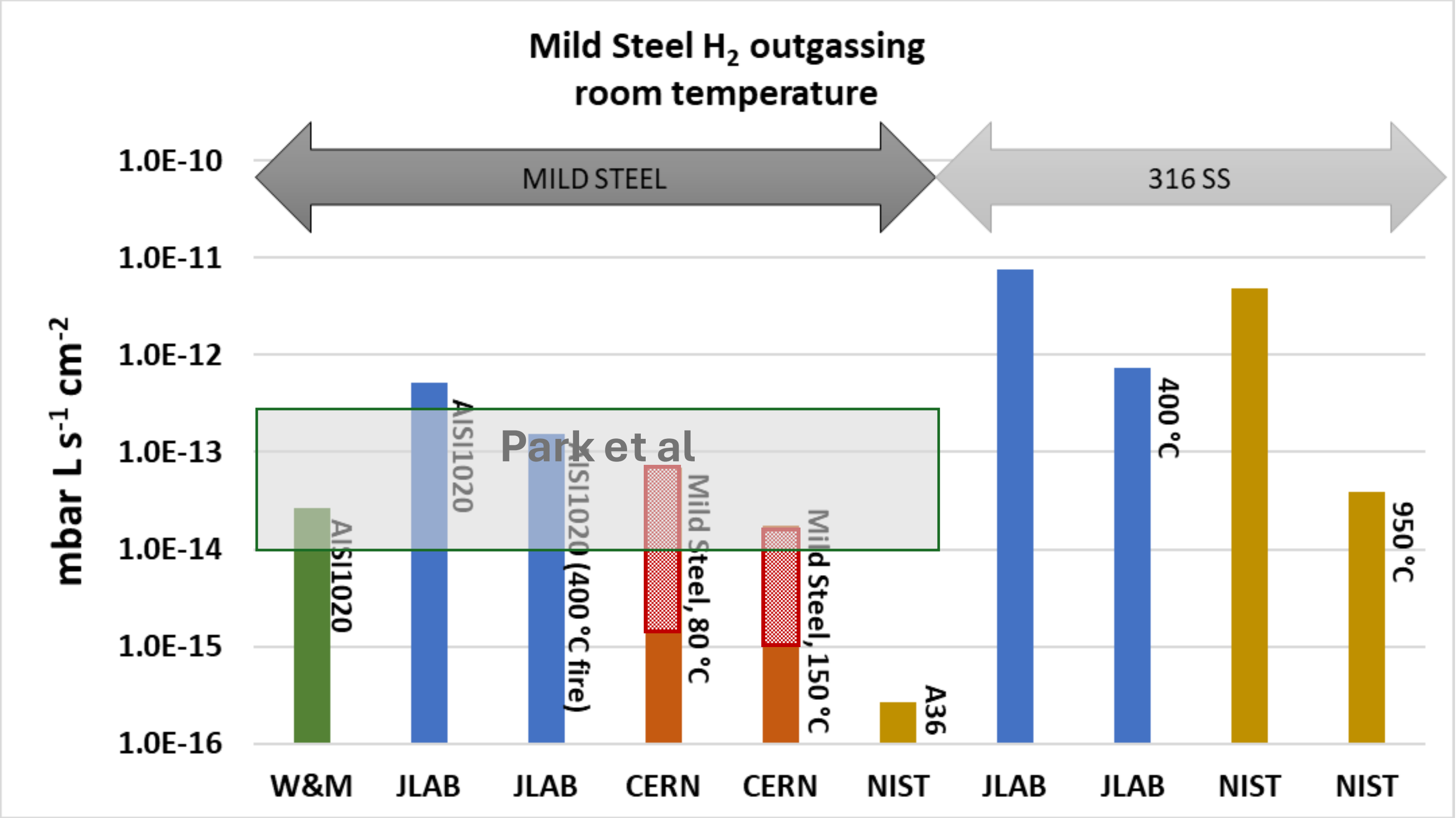


RH process

Mild Steel H_2 outgassing (Fedchak 2023 Summary)

Lab	Mild Steel	mbar L s-1 cm-1
W&M	AISI1020, 150 °C, 48 h bake	2.6E-14
JLAB	AISI1020, 150 °C, 69 h bake	5.2E-13
JLAB	AISI1020 (pre-bake 400 °C), 150 °C, 48 h bake	1.5E-13
CERN	Mild Steel, 80 °C, 48 h	1.5E-15
CERN	Mild Steel, 80 °C, 48 h	7.0E-14
CERN	Mild Steel, 150 °C, 48 h	1.0E-15
CERN	Mild Steel, 150 °C, 48 h	1.7E-14
NIST	A36, 299 K, 100-150 C bake, 5 days	2.6E-16

Lab	Stainless Steel	mbar L s-1 cm-1
JLAB	SS316, 150 °C, 48 h bake	7.6E-12
JLAB	SS316 (pre-bake 400 °C) 150 °C, 49 h	7.3E-13
NIST	316L	4.9E-12
NIST	316L-XHV (950 °C Fire)	3.9E-14



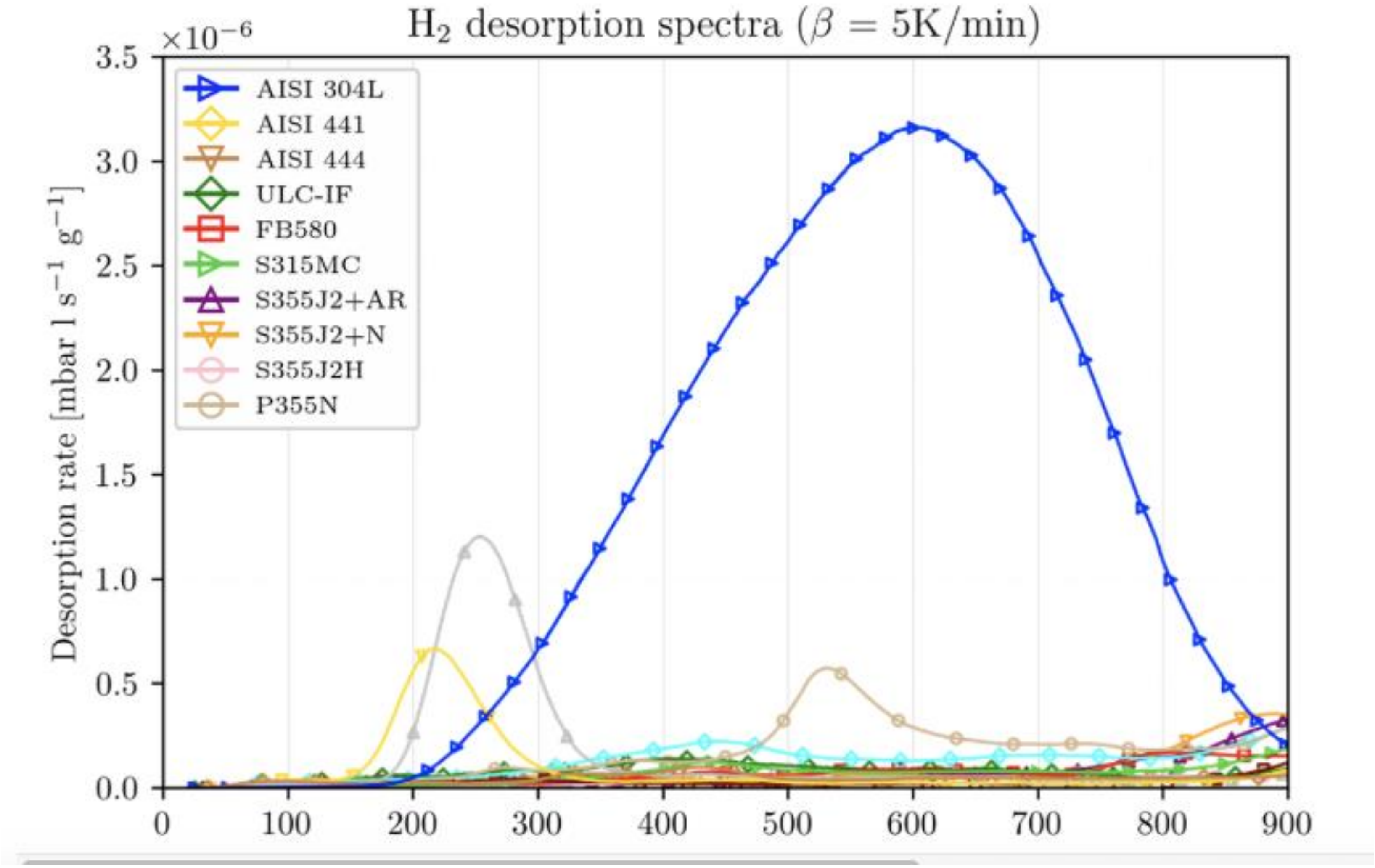
- 150 °C, minimum 48 hour bakes (except where noted)
- All exposed to air before bake
- Other constituents (H_2O, CO CO_2) likely present

Evidence suggests that for a wide variety of mild steels H_2 outgassing will not be a concern for most

Hydrogen desorbed in controlled heating to 900C in vacuum:

304L austenitic steel (blue) as used in LIGO required air bake at 450C to deplete entrained hydrogen.

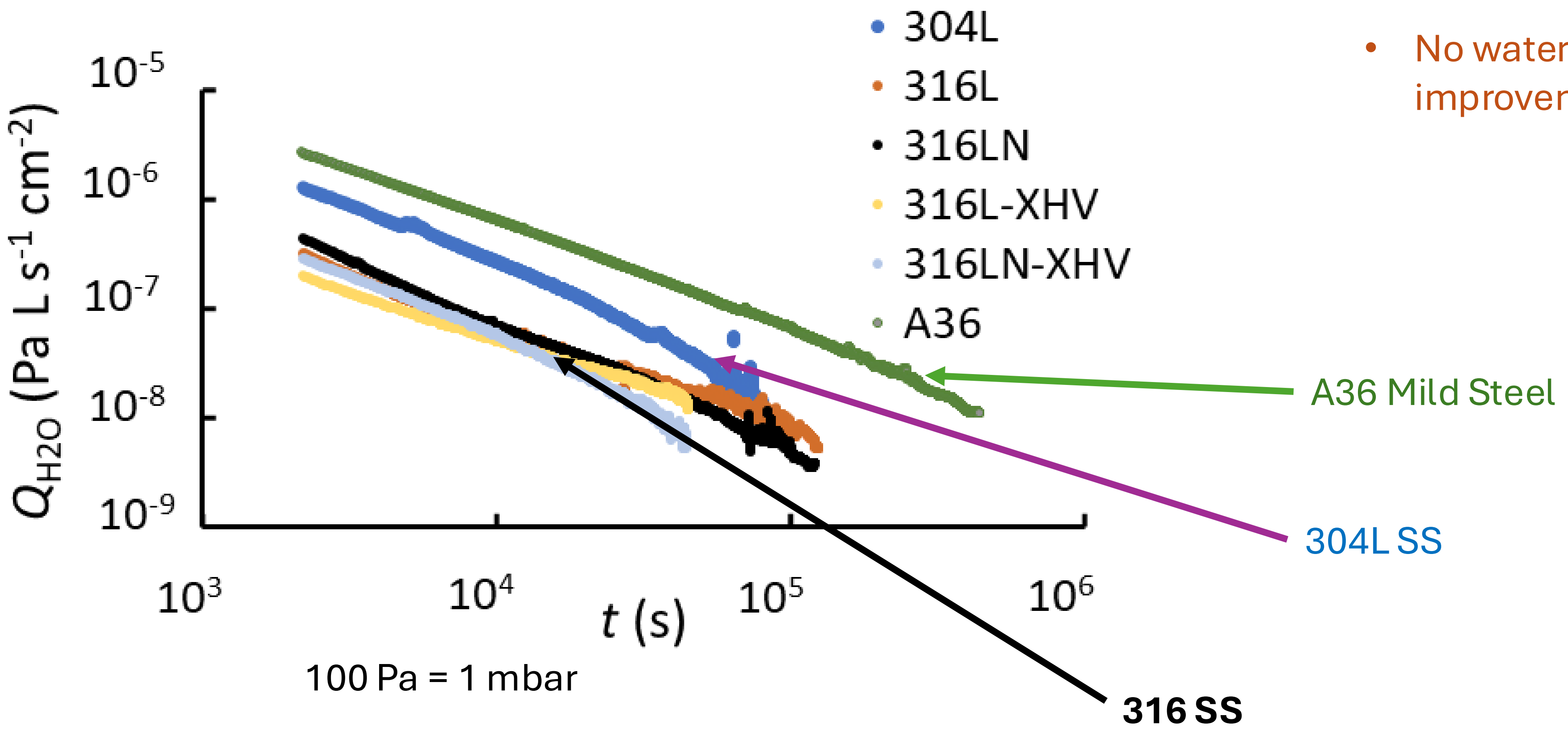
Ferritic (AISI 430, 441 and 444) and mild steels (remaining curves) contain sufficiently low hydrogen to be used without treatment.



Confirming data on H-content from TDS measurements: Scarcia, CERN (January, 2024)

NIST Water Outgassing data (J. Fedchak)

- Exposed to Air
- 316L-XHV and 316LN-XHV vacuum fired 24 h at 950 C.
- No water outgassing improvement



100 Pa = 1 mbar

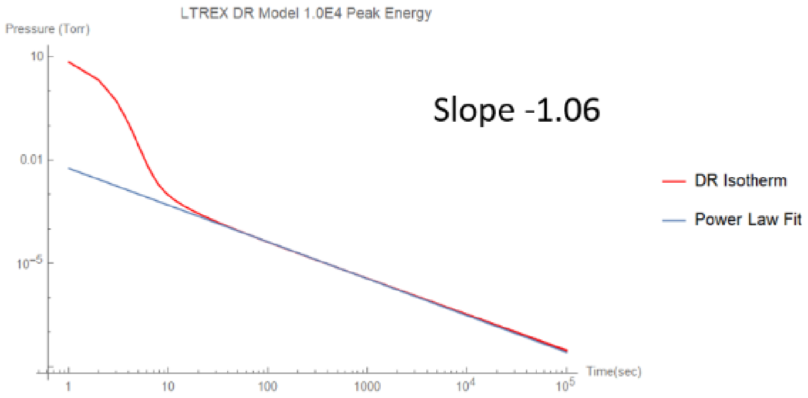
Henkel: Cost advantage of mild steels

Mild steels have these advantages:

- lower cost than SS (by 2-3x)
- Industry in-place with gas/oil pipeline industry
- Production method doesn't incorporate H; yielding H-outgassing lower by 100x than SS, thus, no high temperature pre-bake needed

LTREX Test Chamber at Caltech
Jon Feicht, Melina Fuentes-Garcia

Craning chamber into place
at Caltech synchrotron building



Dubinin-Radushkevich isotherm model predicts p(t). Will verify behavior and adjust model parameters to match actual pumpdown

Working Group 1 Summary: Materials and Surface Studies

D. Henkel and S. Sgobba

- These issues comparing the materials and surface properties of the primary BT candidate materials

  (mild, stainless and ferritic steels)

have had continuing coverage in the on-going LIGO-CE and CERN ET collaborations that were begun after BTW1

Working Group 2 Summary: Design, Mfg., QA and Assembly
Cedric Garion and Guillauma Deleglise

- Significant ground-work was accomplished in this Working Group and subsequent discussions
- Investigated potential schemes and scenarios for

  -BT manufacturing and installation

  -post manufacturing surface treatments

  -leak checking

  -cleanliness and dust control

  -QA

Working Group 3 Summary: Pumping Systems, Valves, Sectorization and Bakeout

Antonio Pasqualetti (Virgo) and Giuseppe Bregliozzi (CERN)

- These subsystems were deemed to be straightforward and not problematic

  -although there is always room for creative cost-cutting!
- Felt no need for a follow-up on this topic at BTW3
- Focus instead on the multi-variable problem of baffle design and implementation

Summing-up the CERN Workshop (BTW2)

- Mild steel presented as possible BT material at the end of BTW1
- Work performed presented at BTW2 and since then has confirmed mild steels a viable BT material

  -advantages in cost, manufacturing capability and low H-content

  -H_2O outgassing probably similar to SS; however there may be lower temperature bakeout advantages (~80C)

  -resistive bakeout not possible because of the conductivity

- This has inspired the subsequent travelling bakeout and dry gas purge tests currently underway at LIGO Caltech
- Fine tuning of the passivation layer on mild steels may have advantages (TBD)

Summing-up the CERN Workshop (BTW2)

Significant papers were presented on:

-Prototype ET beam tubes

-Options for supporting the ET beam tubes

-Initial studies of baffle design issues

-Control and data acquisition systems

-Bakeout equipment and scenarios

-Leak detection equipment and scenarios

-Cost projection models

-Project management structure