NCSX Graphite & Bake-Out Options for Power Handling & Particle Control

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1. Outline

• Results and operational experience from the three predecessor tokamak experiments in the candidate vessel provide useful bench-mark database for NCSX design.

• PDX, PBX, and PBX-M tokamak experiments used unbakeable graphite for power handling in this facility.

• Most recently, PBX-M used a liner-like close-fitting, stainless-steel faced stabilizer shell, and considerable internal hardware.

• The threshold amount of graphite, below which bake-out is not required, and above which 350°C bake-out becomes desirable for this facility is analyzed making use of the PBX-M results.

• The consequences and options for NCSX are explored proceeding from minimal graphite coverage for power handling to total surface coverage with graphite for versatile power handling and a low-Z first wall.

• The results are referenced to the ITER Survey of the 9 Large Tokamaks on Wall Conditioning and Graphite Bakeout.

1. Introduction

• Graphite is used extensively in high power fusion experiments for *Power Handling* and *Particle Control*.

• GRAPHITE
• Useful In Fusion Experiments [1]
+ Low-Z material
+ Becomes stronger as its temperature increases
+ Very strong at high temperatures
+ Thermal and electrical characteristics typical of metals
+ Excellent thermal shock resistance for a brittle material
+ Highly inert to chemical attack at low to moderate temperatures

• Main Difficulties In Fusion Experiments [1]
- Relatively high porosity of manufactured graphite (~20).
- Very large connected internal surface areas ~ 0.1 to 1 m^2/g.
- It is this effective large internal surface area that allows the copious adsorption and desorption of gases which results in the large investment in wall conditioning time required during typical daily operation of high power fusion devices.

[1] R.A. Langley, "Graphite as a Plasma-Facing Material in Fusion Experiments", Proc. IEEE 13th Symposium on Fusion Engineering, V 1, 52, October 2-6,1989, Knoxville, Tennessee.

• It is the prevailing consensus and current practice that a small amount of graphite in a fusion device can be conditioned without high temperature bake-out, but that the use of graphite beyond some threshold amount makes typical conditioning methods impractical and that bake-out at 350 °C is required to achieve acceptable plasma operating conditions within in a reasonable time.[2]

[2] D. Post, "Considerations for Bakeout and Conditioning Specifications for In-vessel Components in ITER", ITER JCT, Jan. 20, 1995 Revised May 2, 1995.

2. Graphite Usage In PDX, PBX, PBX-M

- The initial configuration in the 38 m^3 vessel was PDX (79-83)
  - 250 lbs of graphite for armor and limiters
    - with a total plasma-facing area of about 5.2 m^2
  - Armor tile arrays (4) on the midplane opposite each NBI
    - Covered 70% of the inner wall circumference
      (1.27 cm x10 cm x 12 cm POCO graphite +CVD layer of TiC)
    - Three functions;
      Neutral Beam armor for the vessel inner wall
      Neutral Beam calorimeter
      Toroidal Belt Limiter
  - Small ATJ graphite poloidal limiters were used in the four divertors.

2. Graphite Usage In PDX, PBX, PBX-M (cont)

- Princeton Beta Experiment (PBX)
  and Princeton Beta Experiment-Modified (PBX-M)

  - 4 sets of thick semi-cylindrical ATJ graphite mid-plane armor to protect the mid-plane pusher coil from neutral beam power and in-board plasma scrape-off

  - Power incident on the divertors and passive plates was limited by a poloidal array every 30°

  - These limiters, mounted on the Passive Plate system, were ATJ graphite, 6 cm wide x 2 cm high

  - The Passive Plates were 2.54 cm thick aluminum clad with an explosively bonded layer of 0.110" thick 304-SS

  - The edge-plasma saw ATJ limiters and a 304-SS passive plate surface 2 cm outboard of the limiters

- PBX and PBX-M employed 460 lbs of ATJ graphite for armor and limiters with a total plasma-facing area of about 6.1 m^2

3. PBX-M Liner-Like Passive Plates and Internal Hardware

• PBX-M baseline vacuum characteristics determined by out-gassing from graphite and much internal hardware (might be comparable to NCSX)

Table 3.1 Summary of PBX-M Internal Hardware

Component	Comments
Internal Coils	17 interior magnetic field coils: 1 mid-plane coil, 8 upper coils, and 8 lower coils (IF, DF- 3,-5, -6,-8, and T -1, -2, -3, -4). Each water-cooled coil housed in a vacuum-tight, epoxy-impregnated metal can with associated coil can insulation and support structures
Passive Plate Liner	5 upper and five lower aluminum, 304-SS clad plates. These plates were electrically isolated from the vessel and each other, and each plate had an electrically insulated toroidal gap
Passive Plate Alumina Insulators	400 alumina insulators
Passive Plate Mica Insulators	90 sheets, 24"x30" x 0.030" (84 m^2 of mica surface)
Electrical Feedthroughs	11 electrical feed-throughs (32 pins) for instrumentation
Signal Wire	Total, in-vessel instrumentation wire is about 9280 ft or about 1.8 miles
Signal Wire Insulation	Many wires had special insulation and armor to provide electrical insulation from the vacuum walls, thermal insulation from plasma and/or high temperature components, and electromagnetic shielding.

3. PBX-M Liner-Like Passive Plates and Internal Hardware (cont.)

• This internal hardware created many regions of trapped surfaces and volumes. This greatly increased the potential for water and impurity retention of PBX-M during open periods

• The net effect on the vacuum was to increase the impurity out-gassing surfaces and the amount of impurity trapping volumes

4. PBX-M Vacuum Preparations Before Pump-down

• The opening of the PBX-M vessel for extended maintenance periods exposed the interior surfaces and trapped volumes to atmospheric gases

• Although, the in-vessel work was performed by personnel following standard clean-room and clean vacuum system procedures, these activities introduced significant amounts of water vapor and hydrocarbons

• Prior to closing the vessel, standard vacuum system cleanup procedures were followed. The final scrub of the vessel prior to closing included a through vacuum cleaning and wiping with alcohol

• Many highly dense, confined regions of the interior were not accessible to these manual cleaning procedures

5. PBX-M Initial Pump-down After a Vent

• During an extended opening of the vessel for maintenance, there might be one or more test pump-downs prior to final diagnostic work and the final pump-down.

Table 5.1 PBX-M Pump-down/Conditioning Sequence

Activity	Duration	Pressure/ conditions	Comments
• Pump-down starts using 2600 l/s turbomolecular pump system • Leak checking	2 to 4 wks	from air to mid 10^{-6} Torr	RGA spectrum dominated by water vapor and hydrocarbo out-gassing from the large net internal surfa area & trapped volume
• Mild 50 °C bakeout	1 to 2 weeks	hi 10^{-6} Torr	Hot water circulated in lower dome cooling lines
• Ar GDC [a,b]	1 to 4 days	1-2 Torr	GDC adjusted to s within Passive Plate ca
• Start Ti Getter Pumping	1 to 2 days	mid 10^{-7} Torr	Base pressure decrea by factor of 5 to 10
• Start PDC	1 to 2 days	low 10^{-7} Torr	Continue until can get 150KA circular plasma
• Start Ohmic L-Mode XP's & NB target develop	0.5 to 1 Months	low to mid 10^{-8} Torr	~125 discharges/day 600-1000 ms
• Start NBI & achieve H-Mode	0.5 to 1 Months	low to mid 10^{-8} Torr	Highly dependent on details of Exp Sch.

a) H. F. Dylla *et al*., "Glow Discharge Conditioning the PDX Vacuum Vessel", JVST 17(1), 286(1980)
b). H. F. Dylla, *et al*., "Glow Discharge Techniques for Conditioning High-Vacuum Systems", JVST, A6(3), 1276 (1988).

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6. PBX-M Wall-Conditioning After Starting Plasma Operations

Table 6.1. Summary of PBX-M Daily Operation Activities

Wall Clock Time	Activity	Base Pressure (Torr)
6:30 AM	Start Operations Check-List	low to mid 10^{-7} Torr
7:30 AM	*Start Ti Getters	
8:00 AM	Field-only test shots & NBI conditioning	
8:30 AM	Start Ohmic conditioning	low to mid 10^{-8} Torr
9:30 -10:00 AM	Start Ohmic XP's	
9:30 - 11:00 AM	NBI ready	
6:00 PM	Stop (~125 discharges) Turn-off Ti Getters Secure system for overnight	low to mid 10^{-8} Torr

7. PDX, PBX, PBX-M Experience With Unbaked Graphite

• The PDX, PBX, and PBX-M physics results were paced by the above conditioning procedures.

• For PBX-M, the high-β toroidal and poloidal experiments seemed to be paced by hydrocarbon and other low-Z impurity influxes from divertor-region as the plasma shape (indentation, elongation, X-points, and strike-points) was changed to access new regimes

• Metal impurities from the close-fitting Passive Plate structure, although a concern were perceived as a secondary issue at that time.

• After the IBW induced Core-Confinement (CH) Mode was discovered, it became apparent that metallic impurities were also being confined very well and that metallic influxes needed to be controlled for the next push forward.

• It was not clear, if this impurity influx was due primarily to edge plasma interaction with the entire stainless steel surface of the Passive Plates, or from regions within 1 m of the IBW antennas.

• Cladding the Passive Plates with graphite and additional boronization were being considered.

7. PDX, PBX, PBX-M Experience With Unbaked Graphite (cont.)

•The effect of adding more unbakeable graphite to PBX-M was estimated approximately by assuming a linear relationship between the total weight of graphite in the vessel and the range of typical wall-conditioning times needed from pump-down to reach the first H-mode.

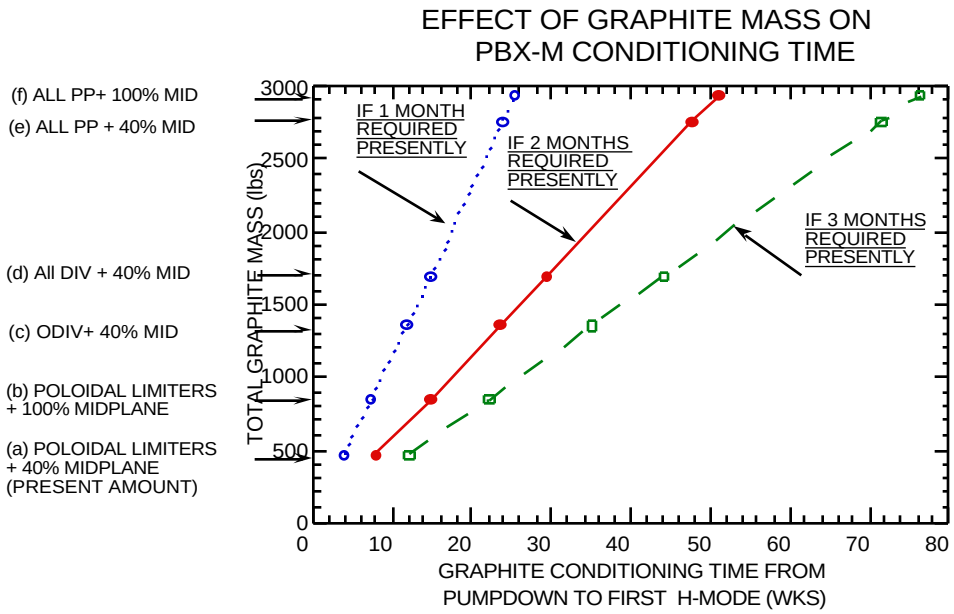

Fig.7.1

• For full coverage, it would take at least 26 weeks of high power neutral beam operation to reach the first H-mode, and probably many more weeks to reach equilibrium conditions.

• Conclusion

With the available auxiliary power levels of the PBX-M system about 500 lbs of graphite could be conditioned sufficiently without baking to achieve the first H-mode in a reasonable number of weeks, but amounts beyond this would require

conditioning times that were a prohibitive fraction of the experimental year.

8. NCSX Power Handling With Half-Liner And Minimal Unbaked Graphite

• Consider a simple NCSX proof of principle design with an in-board semi-poloidal stainless steel Half-Liner to protect in-vessel coils and inner wall from edge plasma heating.

• Let this stainless steel Half-Liner support a toroidal belt limiter, about 0.5 to 1 m wide, and clad with 1.27 cm thick graphite tiles. In addition, let there be a 6 cm wide x 2 cm high graphite poloidal limiter enclosing the plasma every 30°. This design would require about 400 to 600 lbs of graphite.

• If the neutral beam injection angles were such as to allow power to reach the inner limiter, then it would also act as neutral beam armor, similar to that used in PDX [3]. If the neutral beams were aimed tangential then a far wall armor might be needed for low density operation, (about an additional 100 lbs of graphite) although this was never required for PBX-M tangential injection.

[3] H. W. Kugel and M. Ulrickson, “The Design of the Poloidal Divertor Experiment Tokamak Wall Armor and Inner Limiter System”, Nucl Techn./Fus., V2, 712 (1982).

• A total unbaked graphite usage of 400 to 600 lbs, or possibly as high as 700 lbs would be of order that used in PBX-M (460 lbs)

• Using similar high power conditioning procedures, the expected NCSX wall-conditioning requirements would be similar to those indicated in Table 5.1

8. NCSX Power Handling With Half-Liner And Minimal Unbaked Graphite (cont.)

• Under these conditions, the amount of daily operating time devoted to wall-conditioning could be reduced significantly if cooling/heating lines on the rear-face of the Half-Liner were used to provide a mild Bakeout, e.g., 50-120 °C, and aggressive on-going wall-coating deposition were employed.

• The use of this Half-Liner would *maximize pumping conductance* to the 2600 l/s mechanical pumping system, the lower dome 5 m^2 Titanium Gettering system, the four Neutral Beamline 400 Kl/s cyropanel pumping systems, and boron deposition on the Half-Liner and vessel outer wall.

• This design would limit plasma shape changes to those allowed by the graphite power handling coverage. Changes in plasma shape and position would heat unconditioned regions and would likely require a new round of conditioning.

9. NCSX With Full-Liner And Minimal Unbaked Graphite

• The use of the same amount of graphite with a poloidally complete Full- Liner might reduce impurity influx from the vessel outer wall, especially if the Full-Liner would be mildly bakeable while the outside wall was colder.

• A Full Liner would need cutouts for the diagnostic ports, the neutral beam ducts, and RF antennas. If there were open pathways between these cutouts and the lower dome, Titanium Sublimation pumping system could be used.

• The use of staggered poloidal gaps instead of a poloidally continuos Full-Limiter, would provide optically complete coverage while still allowing pumping conductance to the dome and edge region.

• This geometry would be similar to the poloidal gaps in the PBX-M Passive Plate system. While this geometry would reduce outer wall influxes, the net conditioning requirements would be about the same as those for the semi-poloidal Half-Liner, since the same amount of graphite would be involved

10. NCSX Bakeable Full-Liner With Full Graphite Coverage

• A toroidally complete liner capable of supporting the full range of NCSX operating conditions could have a surface area of about 40 m^2. If this area was clad with 1.27 cm thick graphite tiles, it would require about 2000 lbs of graphite.

• Requiring thicker tiles at some locations could easily cause the total graphite mass to approach 3000 lbs. This amount of graphite could be of order the amount indicated in Fig. 7.1 for complete coverage in PBX-M.

• Community consensus based on 20 years of operating experience and current practice is that the required bakeout temperature for outgassing large amounts of graphite is 350 °C*

* D. Post, “Considerations for Bakeout and Conditioning Specifications for In-vessel Components in ITER”, ITER JCT, Jan. 20, 1995 Revised May 2, 1995.

10. NCSX Bakeable Full-Liner With Full Graphite Coverage (cont.)

• The Full-Liner supporting the graphite tiles needs to have cut-outs for the diagnostic ports, the neutral beam ducts, and RF antennas. If there is an *open pathway* between these cutouts and the lower dome, then the Titanium Sublimation pumping system could be used effectively.

• The use of *staggered poloidal gaps* instead of a poloidally continuous Full-Limiter, would provide optically complete coverage while still allowing pumping conductance to the dome and edge region.

• Simple *shutters* at each of the mid-plane cutouts could reduce the cooling requirements on the vessel wall & ducts during bakeout while allowing the vessel mechanical pumping system to exhaust out-gassing during the bakeout.

• Given the difficulty of removing heat from large vessel structural elements, it might be more convenient for NCSX to have *simple radiation shields* between thermally shielded back-side of the first wall and the vessel wall for heat removal, thereby allowing the vessel to remain below 50-100 °C during 350 °C bakeout of the liner graphite.

11. NCSX Impurity Control Considerations

• In addition to sufficient power handling to allow the desired range of experimental configurations, NCSX should have a comprehensive impurity control plan

• This should include suitable pumping systems with sufficiently conductive pumping geometry, sufficient bakeout capability to remove graphite out-gassing as an issue, Glow Discharge Cleaning (GDC) during maintenance periods, automated HeGDC between discharges, and suitable wall coatings such as appropriate boronization[a,] and lithiumization,[b,c] techniques

a) H. W. Kugel *et al*., "Real-time boronization in PBX-M using erosion of solid boronized targets," J. Nucl. Matr. **220-222**, 636 (1995).
b) H. W. Kugel, *et al*., “Development of Lithium Deposition Techniques for TFTR “, Princeton University, Plasma Physics Laboratory Report,PPPL-3270, October 1997 in Proceedings of 17th IEEE/NPSS Symposium on Fusion Engineering, 6-10 October, 1997, San Diego CA.
c) D. K. Mansfield, *et al*., “ DOLLOP: Improved Plasma Performance Using a New Concept for Mitigating the Plasma-Wall Interaction in Fusion Devices”, Bull. Am. Phys. Soc. 42(10), 1972 (1997

12. Summary and Conclusions

• The PBX-M experience with unbaked graphite indicates that with the power levels of the PBX-M system about 500 lbs of graphite could be conditioned sufficiently without baking in a reasonable number of weeks to achieve the first H-mode, but amounts beyond this required conditioning times that were a prohibitive fraction of the experimental year.

• The feasibility of a steady state hot first wall should be explored. If a design is capable of bake-outs for 1-2 weeks, perhaps it could also allow operating with continuously hot walls.

• NCSX liner and graphite designs should include sufficient conductance for adequate pumping, and should be part of an overall impurity control plan.

Appendix I

The physics basis for baking graphite at 350 ° is given in the ITER Report prepared from the draft titled “Considerations for Bakeout and Conditioning Specifications for In-vessel Components in ITER” prepared by D. Post, ITER JCT, Jan. 20, 1995 Revised May 2, 1995. Table 2.5.1 given below lists the conditioning experience of major Tokamaks. The final report was reviewed by the contributors from the major Tokamaks. Fig. 2.5.2 from that report is given below.

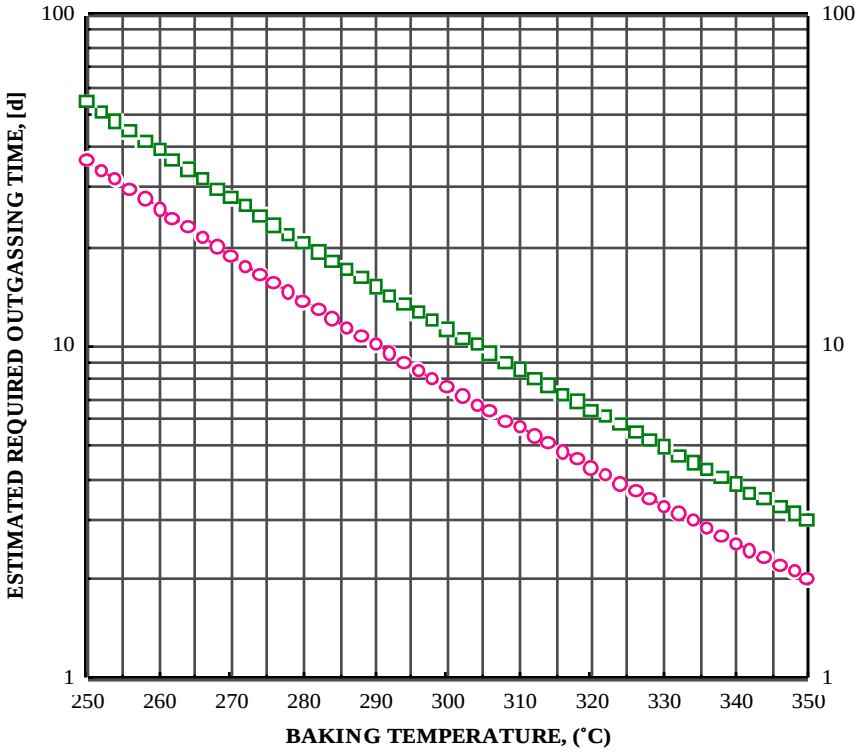

FIGURE 2.5.2 Design range for baking. The range between the two curves includes the uncertainties of the available experimental data and the variation of material properties among different types of carbon-based materials.

Table 2.5.1 Bake-out and operational experience in present tokamaks:

(Temperatures in ^{o}C)

Alcator C-Mod (B. Lipschultz, J. Irby)
Materials: Mo, SS
No conditioning between shots. ECDC (Electron Cyclotron Discharge Cleaning), 1.5 hours every day before run. B conditioning every several weeks done with ECDC. Li pellet conditionig with Li pellets was tried but not found to be helpful.

bakeout:	130°C for 3-5 days	running:	vessel at room temperature tiles up to 300—500°C	between shots:	room temperature

ASDEX/U (J. Neuhauser)
Materials: C, SS
B conditioning overnight every few weeks to months, He glow discharge cleaning between discharges, 150°C baking (only after vessel opening)

bakeout:	150°C	running:	vessel < 60°C tiles<1000°C tile edges< 3000°C	between shots:	<60°C

DIII-D (G. Jackson, D. Hill)
Materials: C, Inconel
He glow discharge conditioning between shots, active pumping system now used. When pumping is used, density control is possible without He glow discharge conditioning. Boronization is done every 1 to 2 months. A lithium pellet injector has recently been insatlled.

bakeout:	350°C	running:	30—700°C (on tiles)	between shots:	≤50°C

JET (G. Janeschitz, G. Vlases, Gabrielle Saibene and Philip Andrew)
Materials: Be, C, Inconel VV
Be evaporation occasionally, presently use in-vessel cryo-pump in which case GDC and other conditioning techniques between shots are not employed

bakeout	initial bakeout at 200°C for 1.5 days, followed by 40°C cooled tile and 320°C bakeout of the rest of the tokamak. With Mark II divertor, baking of divertor is limited to lower temperatures	running	250—320°C for the vessel walls, but tiles may reach 1000°C	between shots:	≥250°C (divertor tiles cooled down to 40°C between shots)

JT-60/U (M. Shimada / M. Nagami / M. Azumi)
Materials: C, SS
Baking at 300ºC is done for 3 days after vacuum vent, normally once or twice a year, high running temperatures help operation, with 300ºC, 3 high T_i shots / hour. With 150ºC, the number of good high T_i shots drops from 3 / hour to 1 / hour. Boronization is done once or twice per year. Normally there is 1 hour of He glow discharge cleaning per 6 hours of operation, with 3 to 7 hours additional per night. There are 5 to 10 minutes of helium TDC after disruptions. Lower chemical erosion occurs with lower wall temperatures (less C impurities)

bakeout:	~300ºC	running:	100—300ºC	between shots:	~200-300ºC (40ºC for water cooled divertor tiles between shots)

T-10 (K. Razumova, G. Notkin)
Materials: Inconel VV, Graphite limiters
8 hours of baking every night, TDC as well, glow discharge sometimes used before boronization

bakeout:	250-300ºC	running:	limiter reaches 250ºC	between shots:	20ºC

T-15 (K. Razumova, G. Notkin)
Materials: SS VV, Graphite limiters
not much operating experience yet, baking planned up to 150, glow discharge beginning to operate

bakeout:	—	running:	limiter up to 40ºC	between shots:	wall at 0ºC

TEXTOR (J. Winter)
Materials: carbon limiters, Inconel liner, stainless vacuum vessel
density control with pumped limiter, active pumping keeps the wall inventory low, conditioning with boron and silicon coatings

bakeout:	350ºC	running:	150-175ºC	between shots:	150ºC

TORE-Supra (C. Grisolia)
Materials: SS, Boronized graphite inner walls (~100m^2), actively cooled graphite (~15m^2)
B conditioning, active pumping help control the wall inventory

bakeout:	210ºC for a few days, D_2 GD, then He GD	running:	150ºC	between shots:	≥150ºC

TFTR (M. Ulrickson)
Materials: C, Inconel
B and/or Li conditioning before operation, disruptive discharge cleaning with glow discharge cleaning

bakeout:	150ºC	running:	40ºC	between shots:	≥40ºC