Electronic Supporting Information

Revisiting the structural homogeneity of NU-1000, a Zr-based Metal-Organic Framework

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Abstract: Synthesis and activation of phase-pure and defect-free metal–organic frameworks (MOFs) are essential for establishing accurate structure-property relationships. Primarily suffering from missing linker and/or node defects, Zr_6-based MOFs can have polymorphs, structures with the identical linker and node but different connectivity, which can create multiple phases in a sample that complicates the characterization. Here, we report the synthesis of phase-pure NU-1000, a mesoporous Zr_6-based MOF that typically contains a significant secondary phase within the individual crystallites. Large biomolecules and smaller inorganic molecules have been installed in NU-1000 as probes to verify the near elimination of the microporous secondary-phase. Obtaining structurally homogenous MOFs will assist the design of new materials with distinct structural features.

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Experimental Procedures

All reagents were purchased from commercial sources and used without further purification. Alexa Fluor 647 labelled insulin (human) was purchased from NanoCS, USA. H_4TBAPy was synthesized following the published procedures.[1]

Powder X-ray diffraction (PXRD) of MOFs were measured at room temperature on a STOE-STADIMP powder diffractometer equipped with an asymmetric curved Germanium monochromator (CuKα1 radiation, λ = 1.54056 Å) and one-dimensional silicon strip detector (MYTHEN2 1K from DECTRIS). The line focused Cu X-ray tube was operated at 40 kV and 40 mA. The activated powder was sandwiched between two Kapton foils and measured in transmission geometry in a rotating holder. Intensity data from 2 to 30 degrees two theta were collected over a period of 15 min. The instrument was calibrated against a NIST Silicon standard (640d) prior to the measurement.

Diffuse reflectance infrared spectra (DRIFTS) were recorded on a Nicolet 7600 FTIR spectrometer equipped with an MCT detector cooled to 77 K. The spectra were collected at 30 °C after heating at 120 °C for 15 min to remove pyhsisorbed water in a KBr mixture under N_2 purge (samples prepared in atmosphere). Pure KBr was measured as the background and subtracted from sample spectra.

Nitrogen isotherm measurements were carried out on a Micromeritics Tristar II 3020 at 77 K. Samples were activated at 100 °C for 1 h and 120 °C for 16 h under vacuum on Micromeritics Smart VacPrep instrument and outgas rate below 0.05 mmHg/min was achieved. Total and micro pore volumes were calculated using DFT model provided by MicroActive software (Micromeritics) by considering pores up to 2 nm and 100 nm, respectively.

Scanning electron micrographs (SEM) images were taken using a Hitachi SU8030 at the EPIC facility (NUANCE Center-Northwestern University). EDS line scans were also obtained on the same instrument. Samples were activated and coated with OsO_4 to ~9 nm thickness in a Denton Desk III TSC Sputter Coater before imaging.

Single-crystal X-ray crystallography: X-ray crystal structure analysis was carried out using a Bruker Kappa APEX II CCD detector equipped Cu $K\alpha$ (λ = 1.54178 Å) microsource with MX optics. The single crystals were mounted on MicroMesh (MiTeGen) with paraton oil. The structure was solved by direct methods (SIR2014),[2] and refined by full-matrix least-squares refinement on F^2 (SHELXL-2017/1)[3] using the Yadokari-XG software package.[4] The disordered non-coordinated solvents were removed using the PLATON SQUEEZE program. Crystallographic data for the updated NU1000 crystal structure in CIF format has been deposited in the Cambridge Crystallographic Data Centre (CCDC) under deposition numbers CCDC-1580411. The data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif (or from the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, U.K.)

Synthesis of NU-1000-TFA (40 mg scale): $ZrOCl_2.8H_2O$ (98 mg, 0.30 mmol) and benzoic acid (2 g, 16.38 mmol) were mixed in 8 mL of DMF in an 8-dram vial and ultrasonically dissolved. The clear solution was incubated in an oven at 100 °C for 1 h. After cooling down to room temperature H_4TBAPy (40 mg, 0.06 mmol) and trifluoroacetic acid (TFA) (40 uL, 0.52 mmol) were added and sonicated for 10 min. The yellow suspension was placed in a pre-heated oven at 100 °C for 18 h. After cooling down to room temperature, yellow polycrystalline material was isolated by centrifuge (5 min, 7500 rpm) and washed with dimethlyformamide (DMF) three times (15 mL each) (soaked ~1 h between washes). An HCl washing step was performed as follows to remove coordinated modulator from the node.

The resulting yellow powder was suspended in 12 mL DMF and 0.5 mL of 8 M aqueous HCl was added. This mixture was heated in an oven at 100 °C for 18 h. After cooling to room temperature, the powder was isolated by centrifugation and washed with dimethlyformamide (DMF) three times (15 mL each) and acetone three times (15 mL each) (soaked ~1 h between washes) and soaked in acetone for additional 16 h. NU-1000 crystals were collected by centrifugation and dried in a vacuum oven at 80 °C for 1 h, and then activated at Micromeritics Smart VacPrep instrument as described above (yield: ~32 mg activated NU-1000).

Synthesis of NU-1000-TFA (4 g scale): $ZrOCl_2.8H_2O$ (9.7 g, 30 mmol) and benzoic acid (200 g, 1.6 mol) were mixed in 600 mL of DMF in a 2-L glass bottle and ultrasonically dissolved. The clear solution was incubated in an oven at 100 ºC for 1 h. In the meantime, H_4TBAPy (4 g, 6 mmol) was added to 200 mL DMF and heated to 100 ºC for 1 h. After cooling down to room temperature, H_4TBAPy solution and trifluoroacetic acid (TFA) (4 mL, 52 mmol) were added to pre-made Zr node containing solution and sonicated for 10 min. The yellow suspension was placed in a pre-heated oven at 120 ºC for 18 h. After cooling down to room temperature, yellow polycrystalline material was collected into six 50-mL centrifuge tubes by multiple cycle of centrifugation (5 min, 7500 rpm) and washed with dimethlyformamide (DMF) three times (~300 mL each) (soaked ~1 h between washes). An HCl washing step was performed as follows to remove coordinated modulator from the node. The resulting yellow powder was suspended in 1300 mL DMF in a 2-L glass bottle and 50 mL of 8 M aqueous HCl was added. This mixture was heated in an oven at 100 ºC for 18 h. After cooling to room temperature, the powder was isolated by centrifugation and washed with dimethlyformamide (DMF) three times (~300 mL each) and acetone three times (~300 mL each) (soaked ~1 h between washes) and soaked in acetone for an additional 16 h. NU-1000 crystals were collected by centrifugation and dried in a vacuum oven at 80 ºC for 1 h, and then activated at Micromeritics Smart VacPrep instrument as described above. (yield: ~5.5 g activated NU-1000). (200 mg and 2 g scale synthesis can be performed following this procedure by scaling down all reagents accordingly.)

Synthesis of NU-1000-TFA single crystals: $ZrCl_4$ (70 mg, 0.30 mmol) and benzoic acid (2 g, 16.38 mmol) were mixed in 6 mL of diethlyformamide (DEF) in an 8-dram vial and ultrasonically dissolved. The clear solution was incubated in an oven at 100 ºC for 1 h. In the meantime, H_4TBAPy (40 mg, 0.06 mmol) was added to 4 mL DEF and heated to 100 ºC for 1 h. After cooling down to room temperature, H_4TBAPy solution and trifluoroacetic acid (TFA) (40 uL, 0.52 mmol) were added to pre-made Zr node containing solution and sonicated for 10 min. The yellow suspension was placed in a pre-heated oven at 120 ºC for 24 h. This method yields ~100–150 micron NU-1000 single crystals.

PW_{12}@NU-1000 was prepared similar to the previously reported procedure.[5] In a centrifuge tube, to a solution of 60 mg $H_3PW_{12}O_{40}$ in 5 mL deionized H_2O, 10 mg of NU-1000 or NU-1000-TFA was added. The mixture was sonicated for 1 min and left at room temperature for 3 days with infrequent agitation every few hours. The suspension was then washed with water three times before being washed with acetone three times. The solid was dried in an 80 °C vacuum oven for 2 hours prior to additional characterization. POM loading (0.8 POM per node) was determined by digestion in 3:1 sulfuric acid: 30% hydrogen peroxide.

Atomic Layer Deposition (ALD) of Mo on NU-1000

A commercial ALD reactor (Savannah S100, Cambridge Nanotech, Inc) was used for vapour-phase deposition. Approximately 5 mg of activated material (NU-1000 or NU-1000 TFA) was placed in a custom-made stainless-steel powder sample holder. The sample holder was placed in the ALD reaction chamber set at 110 °C and allowed to equilibrate for 30 min under 5 sccm of N_2 flow. The molybdenum precursor ($Mo(CO_6)$) was heated to 50 °C to generate sufficient vapour pressure. Due to the high porosity and surface area of NU-1000, quasi-static exposures are required to allow the precursor to diffuse through the material. This is accomplished by including a stop-valve between the reactor chamber and the vacuum pump. Closing the stop-valve before pulsing the $Mo(CO)_6$ precursor isolates the reaction chamber from the vacuum pump allowing sufficient time for the precursor to react with the MOF crystallites. The timing sequence t_1–t_2–t_3 (all times in s), where t_1 is the precursor pulse time, t_2 is the exposure time after the stop-valve is closed, and t_3 is the purge time after the stop-valve is reopened, was used for $Mo(CO)_6$ (1–240–240) and water vapour (0.015–120–120). Each $Mo(CO)_6$ pulse was repeated 15 times to fully saturate the reactive sites on the nodes before moving onto the water pulses which were repeated two times.

Insulin encapsulation and Confocal experiments

Activated NU-1000 crystals (3 mg) were treated with labeled insulin solution (in DI water, 1 mg/mL) for 1 day at room temperature to encapsulate insulin647. Insulin647 distribution was monitored by using confocal laser scanning microscopy on a Leica TCS SP5. Two-dimensional (xy) concentration profiles of insulin647 taken at the center layer within the crystal of NU-1000 were acquired on a Leica-SP5 CLSM.

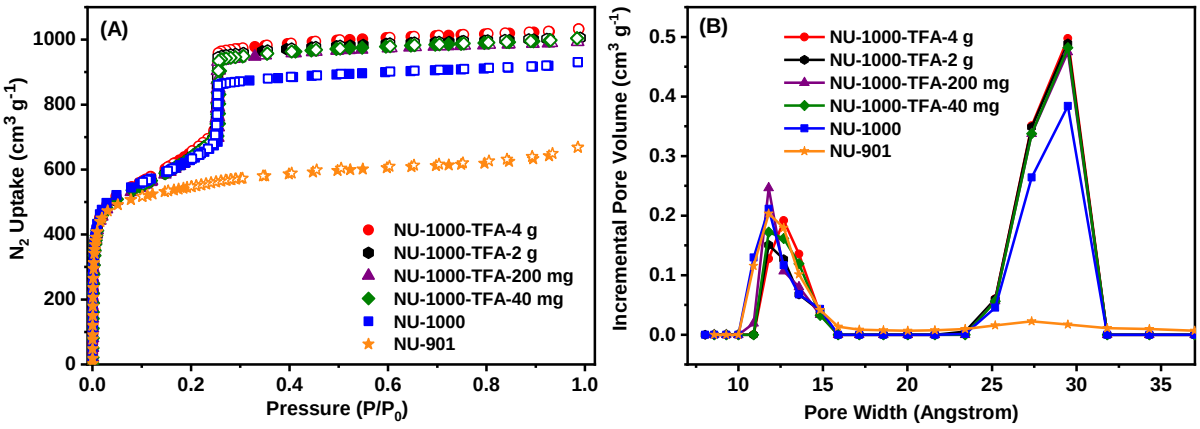

Figure S1. N_2 isotherms (A) and corresponding pore size distributions (B) of NU-1000-TFA (40 mg, 200 mg, 2 g and 4 g scales), NU-1000 and NU-901. N_2 adsorption isotherms shows the agreement between different scale synthesis of NU-1000-TFA.

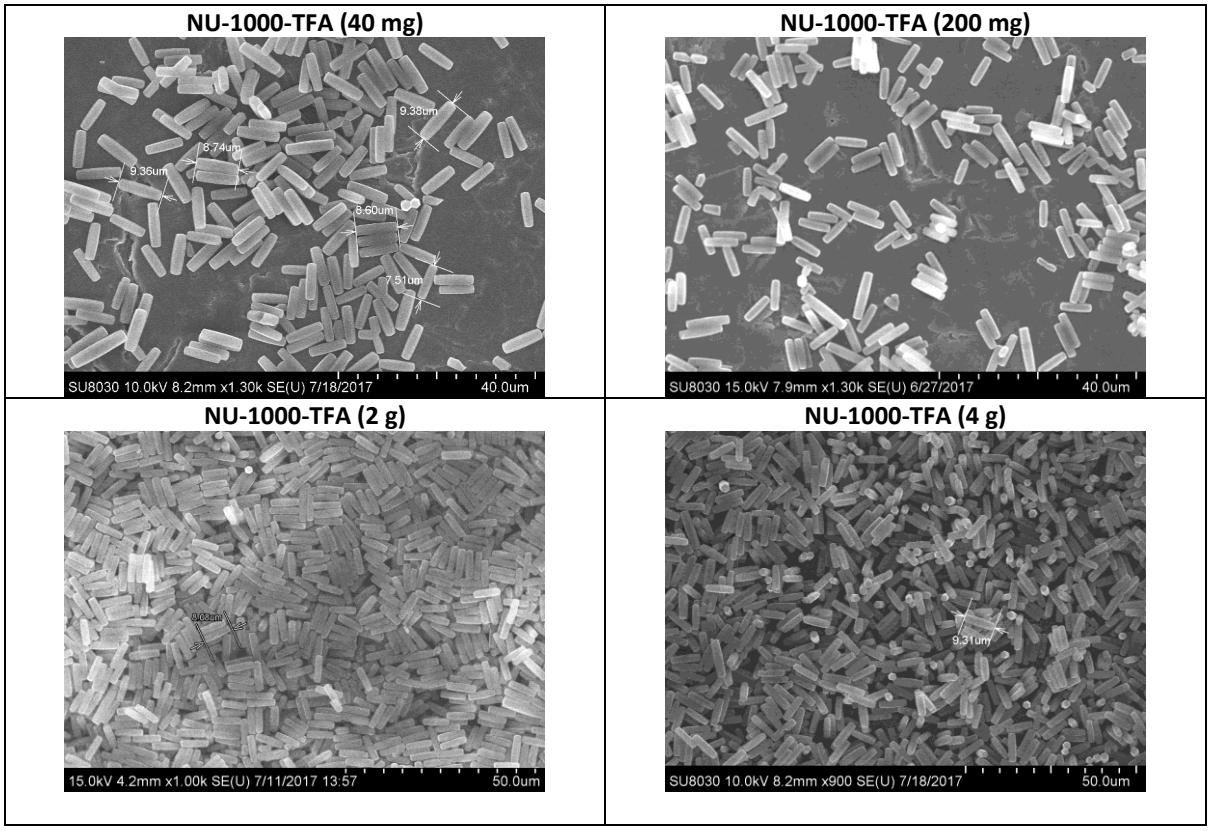

Figure S2. SEM images of different scale syntheses of NU-1000-TFA.

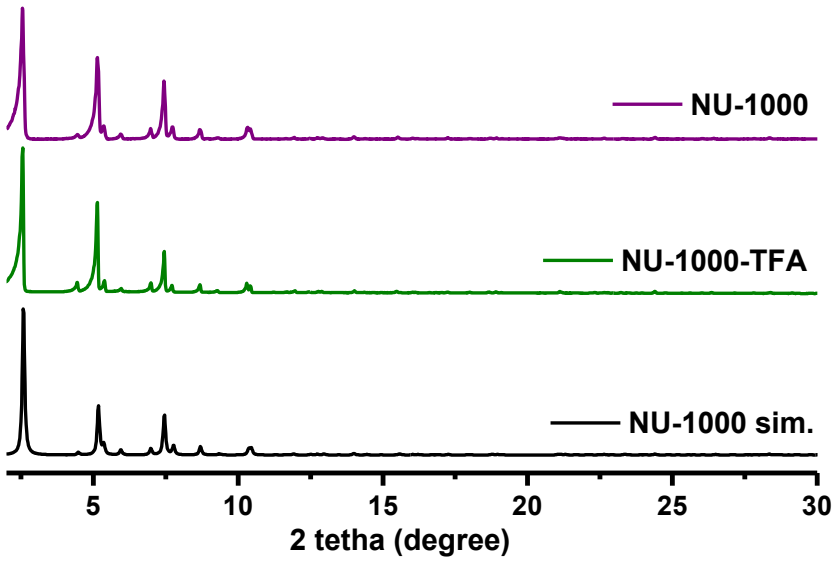

Figure S3. PXRD patterns of NU-1000 and NU-1000-TFA.

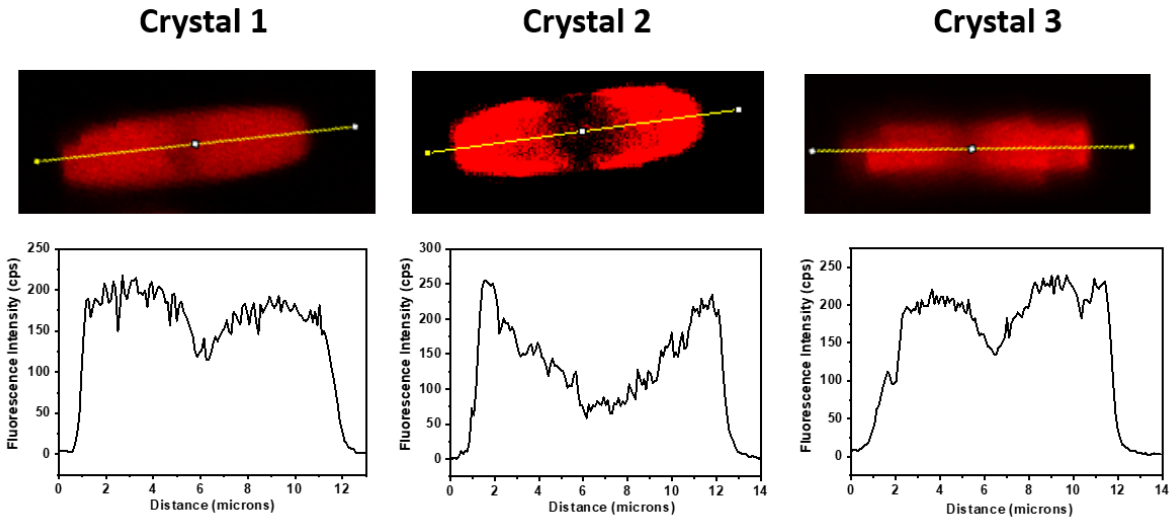

Figure S4. Confocal laser scanning microscopy (CLSM) images (top) plots of fluorescence intensities (bottom) of NU-1000 after installation of insulin tagged with a fluorescent probe for 1 day at room temperature. The similar trend of secondary phase containing center where insulin cannot diffuse easily can be detected in multiple crystals.

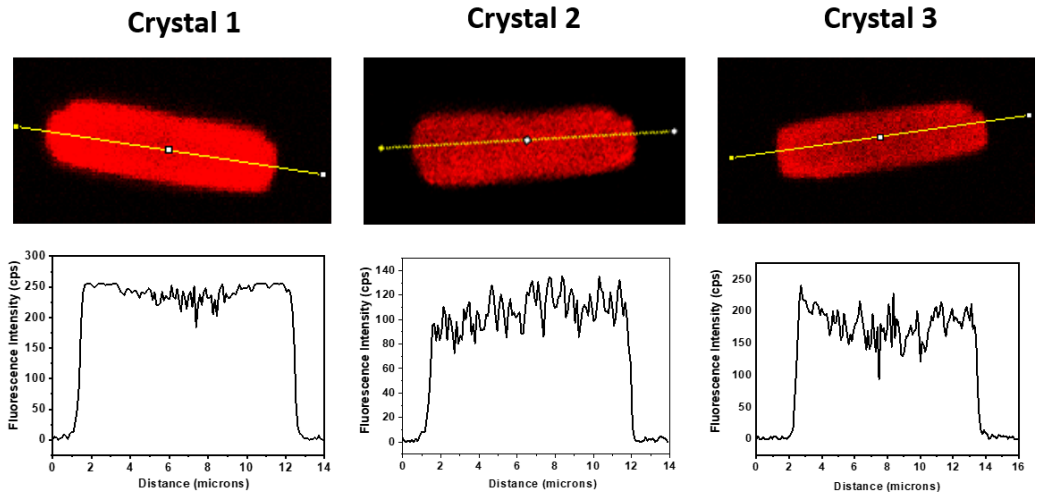

Figure S5. Confocal laser scanning microscopy (CLSM) images (top) plots of fluorescence intensities (bottom) of NU-1000-TFA after installation of insulin tagged with a fluorescent probe for 1 day at room temperature. The similar trend of nearly homogenous distribution of insulin can be detected in multiple crystals.

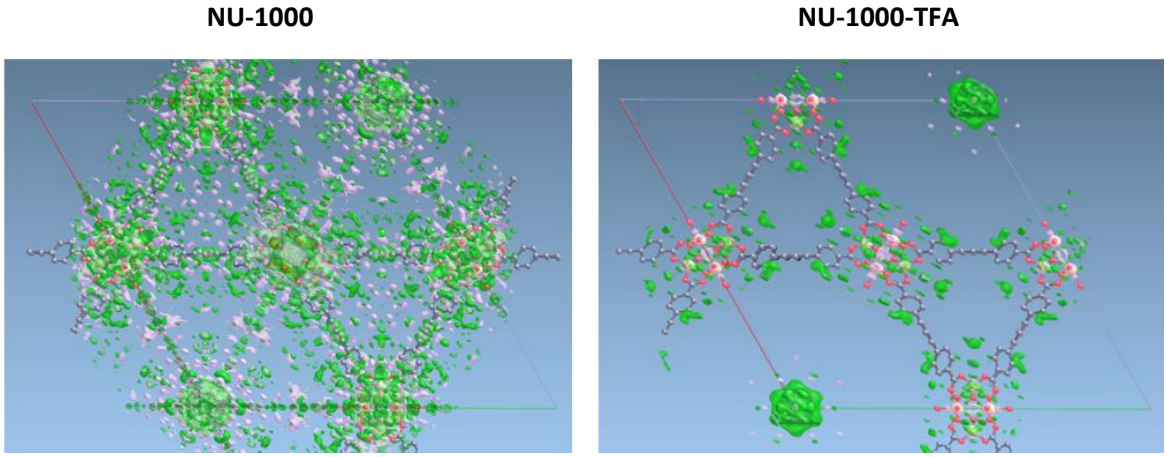

Figure S6. F_o–F_c contour maps in the *ab* plane of NU1000 and NU-1000-TFA (before using SQUEEZE program). The electron densities due to the secondary frameworks are visualized. Counters are from NU-1000 –0.96 to 0.96 eA^{-3} in steps of 0.16 eA^{-3}and NU-1000-TFA –0.64 to 0.64 eA^{-3} in steps of 0.16 eA^{-3}, respectively. The counter maps were calculated using ShelXle software.[6] The final *R* and GOF values for the crystal data of NU-1000 and NU-1000-TFA were as following:

NU-1000: [before SQUEEZE] R_1 ($I < 2\sigma(I)$) = 0.3566, wR_2 (all data) = 0.7159, GOF = 3.594**;** [after SQUEEZE] R_1 ($I < 2\sigma(I)$) = 0.1629, wR_2 (all data) = 0.4852, GOF = 1.905

NU-1000-TFA: [before SQUEEZE] R_1 ($I < 2\sigma(I)$) = 0.1127, wR_2 (all data) = 0.3494, GOF = 1.174**;** [after SQUEEZE] R_1 ($I < 2\sigma(I)$) = 0.0616, wR_2 (all data) = 0.1715, GOF = 1.033

The SCXRD analysis resulted in the same refined structure with improved data quality in NU-1000-TFA (the final *R* values of R_1 ($I < 2\sigma(I)$) = 0.0616 and wR_2 (all data) = 0.1715, and GOF = 1.033) compared NU-1000 (the final *R* value of R_1 ($I < 2\sigma(I)$) = 0.1216 and wR_2 (all data) = 0.3858, and GOF = 1.737).[7] As seen from above residual electron density maps of NU-1000 and NU-1000-TFA crystals, about 25% of pores were estimated to occupied in the case of NU-1000 (left). On the other hand, the updated procedure in this report (NU-1000-TFA, right) indicated the much smaller residual electron density in the mesopore, which is estimated to be around ~6% of the secondary framework inside. The actual density of secondary framework could be lower in NU-1000-TFA when using DMF as a solvent; however, DMF method did not yield large single crystals.

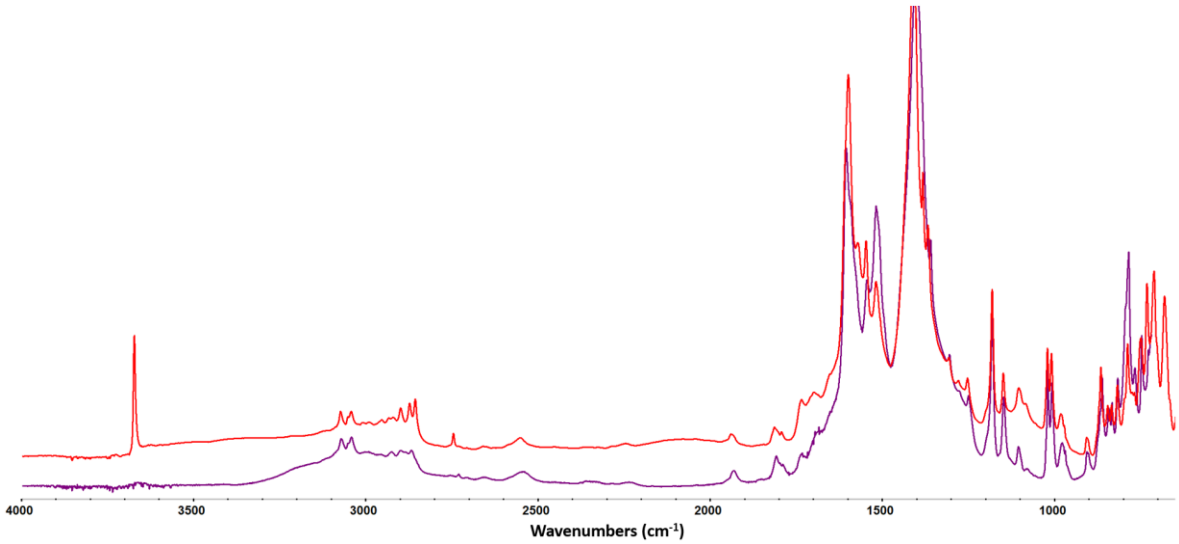

Figure S7. Diffuse reflectance infrared spectra (DRIFTS) of NU-1000-TFA at 120 ºC (top) and 250 ºC after 16 h (bottom). The peak at 3672 cm^{-1} which corresponds to –OH groups vanishes upon thermal treatment due to complete dehydration. NU-1000, on the other hand, can have some residual –OH groups on the node upon the same thermal treatment which can be attributed to presence of the secondary-phase discussed in the manuscript.[7]

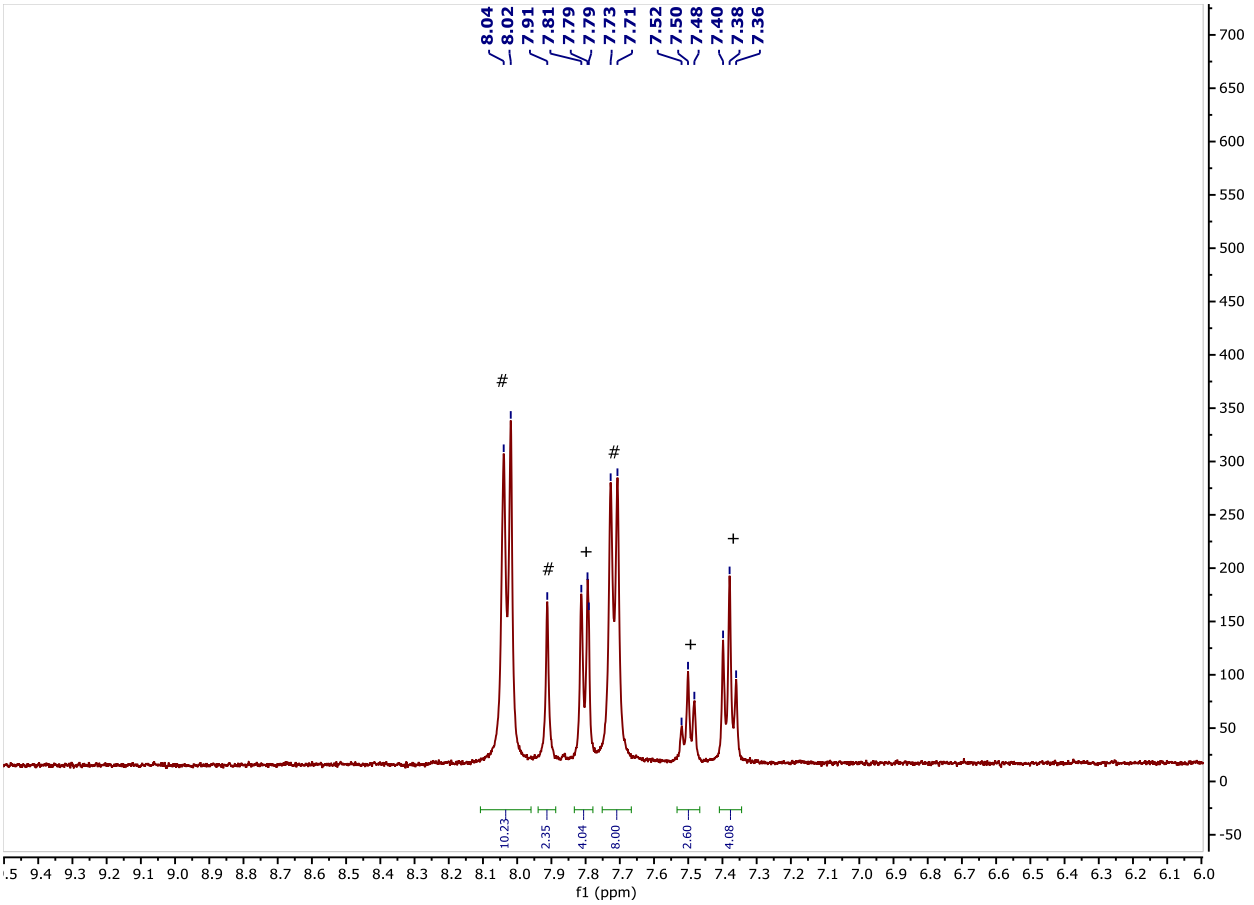

Figure S8. ^{1}H NMR spectrum of as synthesized NU-1000-TFA digested in D_2SO_4 and diluted with DMSO. Corresponding peaks of TBAPy ligand (#) and benzoic acid (+). There is 4±0.08 benzoate ligand per Zr_6 node which suggests no or negligible amount of TFA on the node.

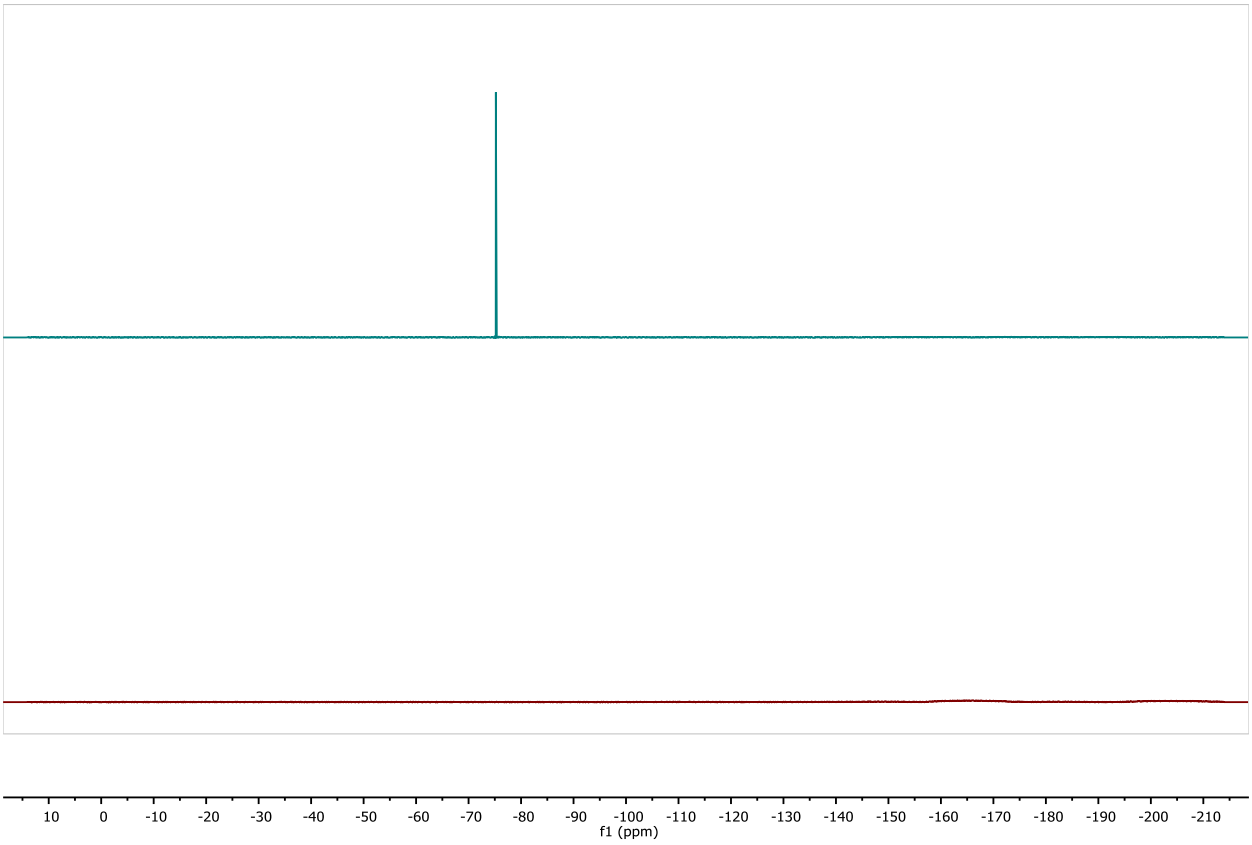

Figure S9. ^{19}F NMR spectra of as synthesized NU-1000-TFA digested in D_2SO_4 and diluted with DMSO (bottom) and the same sample after addition of 5 uL of 1% TFA in DMSO (top) which indicates that no detectable TFA can be found in digested MOF sample.

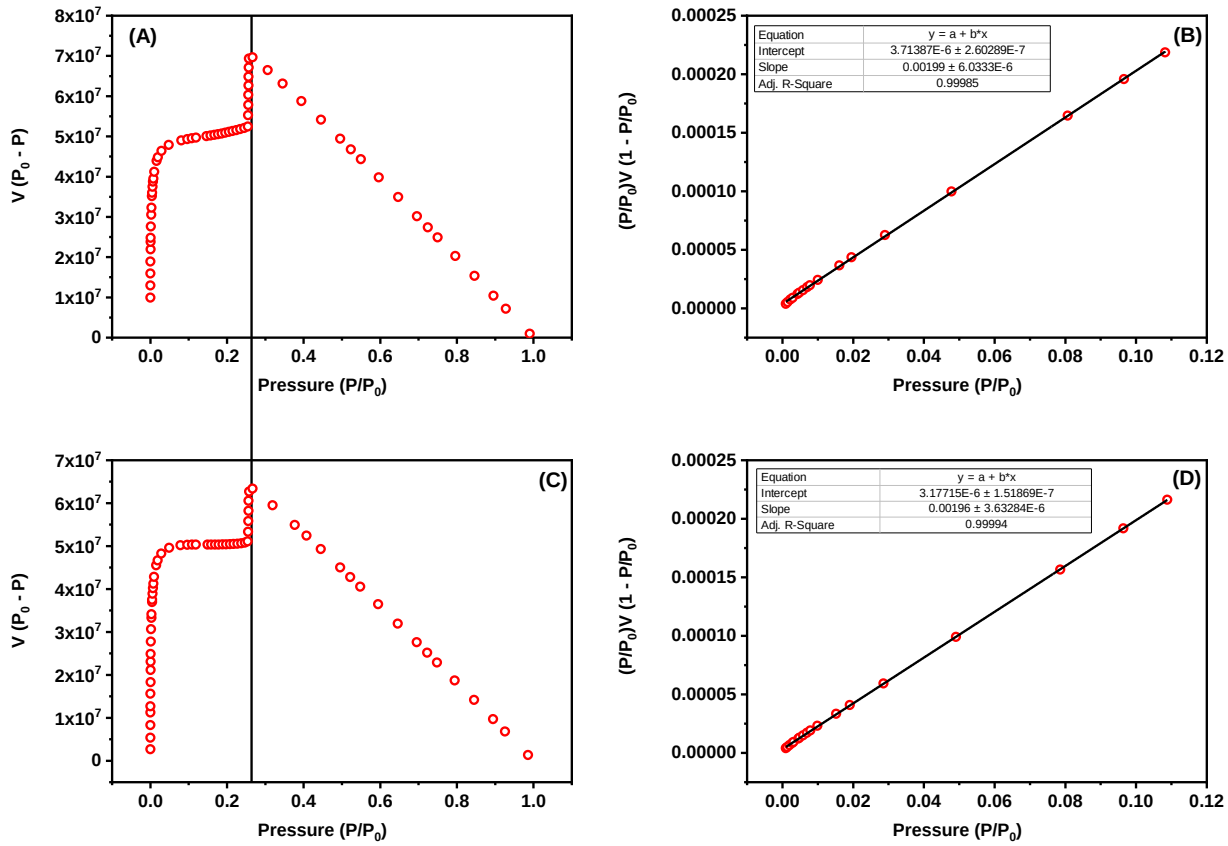

Figure S10. BET area calculation for NU-1000-TFA and NU-1000 from measured nitrogen isotherm at 77 K.[8] (A) and (C) Rouquerol BET plots where the data points to the left of the black line can be used; (B) and (D) linear P/Po range BET plots for NU-1000-TFA and NU-1000, respectively.

References

1. Wang, T. C.; Vermeulen, N. A.; Kim, I. S.; Martinson, A. B.; Stoddart, J. F.; Hupp, J. T.; Farha, O. K., Scalable synthesis and post-modification of a mesoporous metal-organic framework called NU-1000. *Nat. Protoc.* **2016,** *11* (1), 149-162.
2. Burla, M. C.; Caliandro, R.; Carrozzini, B.; Cascarano, G. L.; Cuocci, C.; Giacovazzo, C.; Mallamo, M.; Mazzone, A.; Polidori, G., Crystal structure determination and refinement via SIR2014. *J. Appl. Crystallogr.* **2015,** *48* (1), 306-309.
3. Sheldrick, G. M., Crystal structure refinement with SHELXL. *Acta Crystallographica Section C: Structural Chemistry* **2015,** *71* (1), 3-8.
4. Kabuto, C.; Akine, S.; Nemoto, T.; Kwon, E., Release of software (Yadokari-XG 2009) for crystal structure analyses. *Nihon Kessho Gakkaishi* **2010,** *51*, 218-224.
5. Buru, C. T.; Li, P.; Mehdi, B. L.; Dohnalkova, A.; Platero-Prats, A. E.; Browning, N. D.; Chapman, K. W.; Hupp, J. T.; Farha, O. K., Adsorption of a Catalytically Accessible Polyoxometalate in a Mesoporous Channel-type Metal–Organic Framework. *Chem. Mater.* **2017,** *29* (12), 5174-5181.

6. Hübschle, C. B.; Sheldrick, G. M.; Dittrich, B., ShelXle: a Qt graphical user interface for SHELXL. *J. Appl. Crystallogr.* **2011,** *44* (6), 1281-1284.
7. Mondloch, J. E.; Bury, W.; Fairen-Jimenez, D.; Kwon, S.; DeMarco, E. J.; Weston, M. H.; Sarjeant, A. A.; Nguyen, S. T.; Stair, P. C.; Snurr, R. Q.; Farha, O. K.; Hupp, J. T., Vapor-Phase Metalation by Atomic Layer Deposition in a Metal-Organic Framework. *J. Am. Chem. Soc.* **2013,** *135* (28), 10294-10297.
8. Wang, T. C.; Bury, W.; Gómez-Gualdrón, D. A.; Vermeulen, N. A.; Mondloch, J. E.; Deria, P.; Zhang, K.; Moghadam, P. Z.; Sarjeant, A. A.; Snurr, R. Q.; Stoddart, J. F.; Hupp, J. T.; Farha, O. K., Ultrahigh Surface Area Zirconium MOFs and Insights into the Applicability of the BET Theory. *J. Am. Chem. Soc.* **2015,** *137* (10), 3585-3591.