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Hollow Fiber Permeable Membrane Technology for OBIGGS, A System Optimization

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Introduction

OBIGGS, or On Board Inert Gas Generating Systems, is a device or set of components on an aircraft that utilizes one of several different types of technology to provide a supply inert gas for the primary purpose of removing or displacing the explosive atmosphere in the fuel tank ullage. The three primary types of technology that are currently in use today are first, a system that utilizes a stored supply of Liquid Nitrogen, second, PSA or Pressure Swing Absorption, and third, Polymeric Hollow Fiber Permeable Membranes (HFPM). The focus of this paper will be to show the methodology of configuring a system using HFPM taking maximum advantage of membrane performance and minimizing the impact on the aircraft systems. The results of this type of analysis will show how OBIGGS can be enhanced by using multiple membrane modules that employ different permeability's and selectivity's for the hollow fiber to provide a significant benefit to OBIGGS performance and system weight.

There are two primary tools that were used in the fuel tank analysis presented here. The first is a fuel tank ullage oxygen analysis program that computes the oxygen concentration of the fuel and ultimately in the ullage space as function of mission time. The original version of this program was titled "ULLAGE" and it is the FORTRAN based program for the X86 Intel computer platform that is completely described in a U.S. Air Force document AFWAL-TR-2060 v. 1. The software allows consideration of fuels with different oxygen and nitrogen Ostwald coefficients, vapor pressures, and at a wide range of temperatures. Also, it considers scrubbing the fuel and ullage, mixing and stirring, fuel tank geometry and if it is pressurized or vented. It is a very comprehensive tool for this type of analysis. The version used in this analysis is titled UMacV1 and is basically the same code as ULLAGE, ported for the Macintosh computer platform. UMacV1 also differs from the ULLAGE due to an enhancement that was added to allow for the fuel scrub feature to run for a variable amount of time of the mission instead of the entire length.

The other tool used for the analysis is a computer permeation model for selecting and sizing the hollow fiber permeable membrane modules. This program is called "PERMAL", and it is also a FORTRAN Based program that calculates the Nitrogen Enriched Air (NEA) flow rates, required feed air, and pressure drop across the membrane module based on the membrane inlet operating conditions. (PERMAL is owned solely by Air Liquide - MEDAL.) The membranes considered for use as part of the analysis are air separation hollow fiber membranes that are currently available in industry today.

To gain a complete understanding of the analysis, knowledge of how polymeric permeable hollow fiber membranes and how they work is important to being able to optimize the system for the technology.

Membrane Structure and Performance.

The Polymeric Hollow Fiber Permeable Membranes currently manufactured for (N_2) nitrogen separation from compressed air are essentially a molecular filter and today's modern membranes are manufactured using several different techniques. This discussion is going to be limited to Asymmetric composite type membranes which are one of the modern membrane's in wide use today. Air Liquide - MEDAL manufactures an air separation membrane such as this and their membranes are a multilayer laminate hollow fiber that is manufactured with an efficient single-step coextrusion solution-spinning process developed by DuPont. The separation efficiency, permeation rates, and mechanical durability of the membrane are optimized via the selection of high-performance polymers for each layer. The selection of these polymers is based on years of dedicated research that included the testing of thousands of different polymers for both permeance and selectivity. Polymers are classified by their glass-transition temperature where the glassy type have high-Tg, are easily manufacturable, and are extremely durable in gas separation service. With few exceptions, all of the membranes in service for gas separation today are glassy polymers.

The terms permeance and selectivity are used to define the membrane performance. Permeance of a gas across a polymeric membrane is based on the solubility of the gas in the polymer as well as the rate of the gas diffusion through the membrane. That is, in order for a gas to permeate across the membrane, the gas must dissolve in the membrane material, diffuse across the thickness of the membrane layer, and then desorb into the permeate phase. The rate of solution and desorption in the membrane material are very fast, so the limiting step to the rate of flow across the membrane is the rate of diffusion within the polymer. Each constituent of a mixed gas, like air, has its own flow rate values or permeance across the membrane. For air there are values for the nitrogen and oxygen permeances, and the ratio of these flow rates is a measure of the efficiency at which the membrane will operate. The ratio of these permenaces values is called selectivity.

The membrane performance is also a function of pressure across the membrane separation layer, and with pressure there is a strong dependence. Simply stated, for OBIGGS, feed pressure is most significant feature of the system that can impact performance. The higher the system operating pressure, the more NEA flow per unit surface area is available. This increased flow rate can be directly translated into a lower system weight for the OBIGGS.

Earlier it was mentioned that the fiber has a composite structure. To give you a better idea of what the fiber looks like, refer to Figure 1 below. The picture is a cross section of a typical permeable hollow fiber magnified 1500 times. Currently the technology exists to manufacture hollow fiber, like the one shown in the picture, with outside diameters in the range of 600 to 150 µm and inside diameters from 500 to 80µm, depending on the application. The bulk of these types of fiber are a rugged porous support layer, supporting a thin, dense highly selective skin where the gas separation takes place. The total thickness of this skin is only a few microns, and it is at the outer skin of this layer, whose thickness is measured in Angstrom, that determines the membrane performance. As is, these fibers can operate at pressures up to 250 psig and temperatures up to 100°C (212°F).

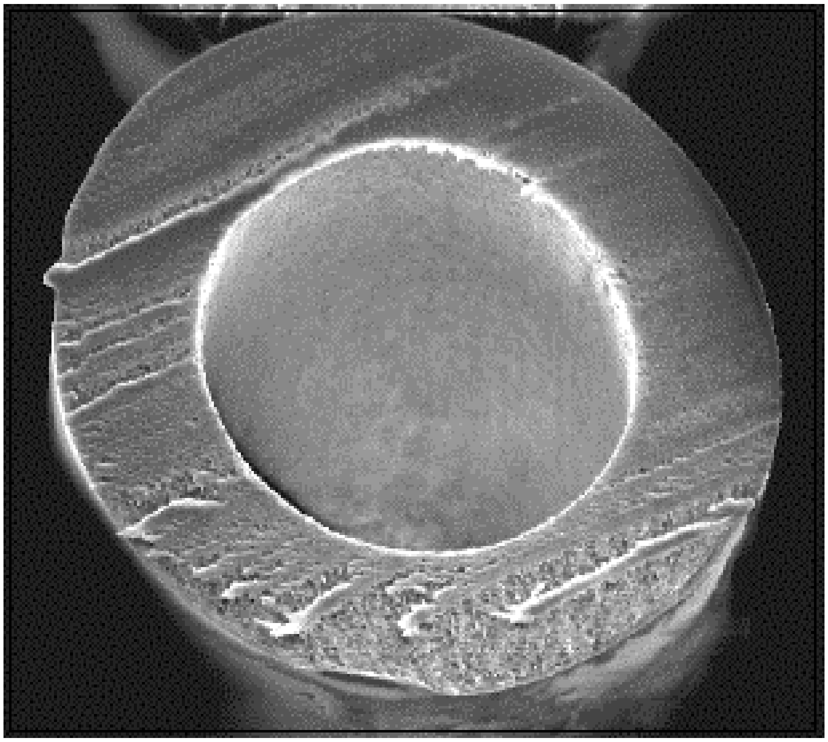


Figure 1.
Fiber Cross Section

A schematic how a typical HPFM module can be seen below In figure 2. The HPFM technology is passive by definition, that is there are no moving parts required for the gas separation to take place. All that is needed is for compressed air to be introduced at the feed end of the module at the proper temperature and pressure, and by regulating the NEA flow, the product gas will be at the proper oxygen level. A by product of the membrane performance is that dew point of the NEA is considerably lower than the feed air. This is due to the fact that the water vapor in the feed air is more permeable than the oxygen (by approximately 10X). This means the NEA to be directed into the fuel tank is very dry, even if the feed air is fully saturated with water.

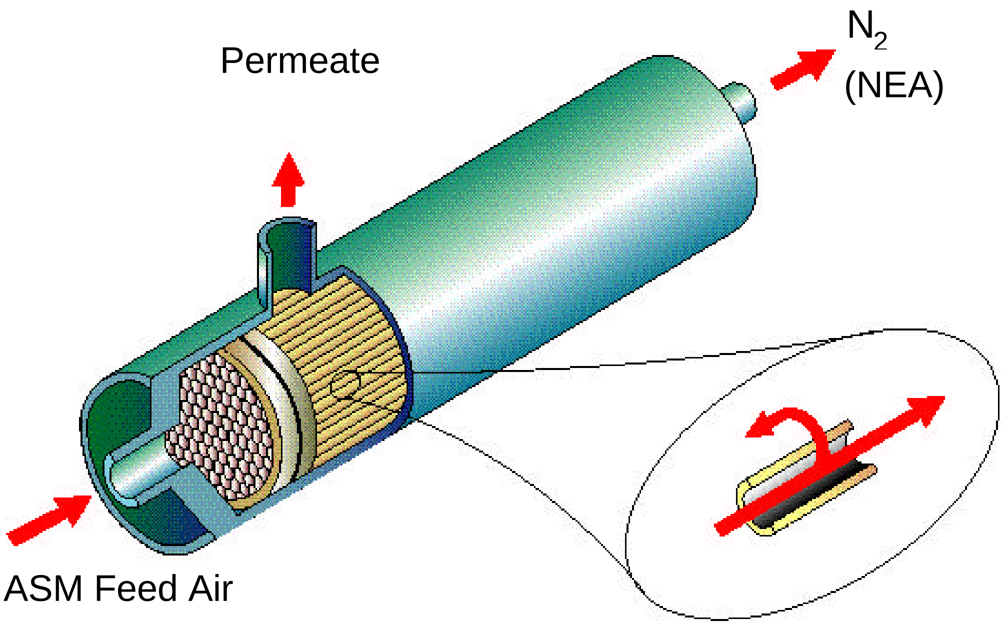


Figure 2.
Membrane Module Schematic

Fuel Tank Analysis.

The aircraft and mission profile used in the analysis is the long mission for the large commercial transport aircraft as defined by the Fuel Tank Harmonization Working Group.

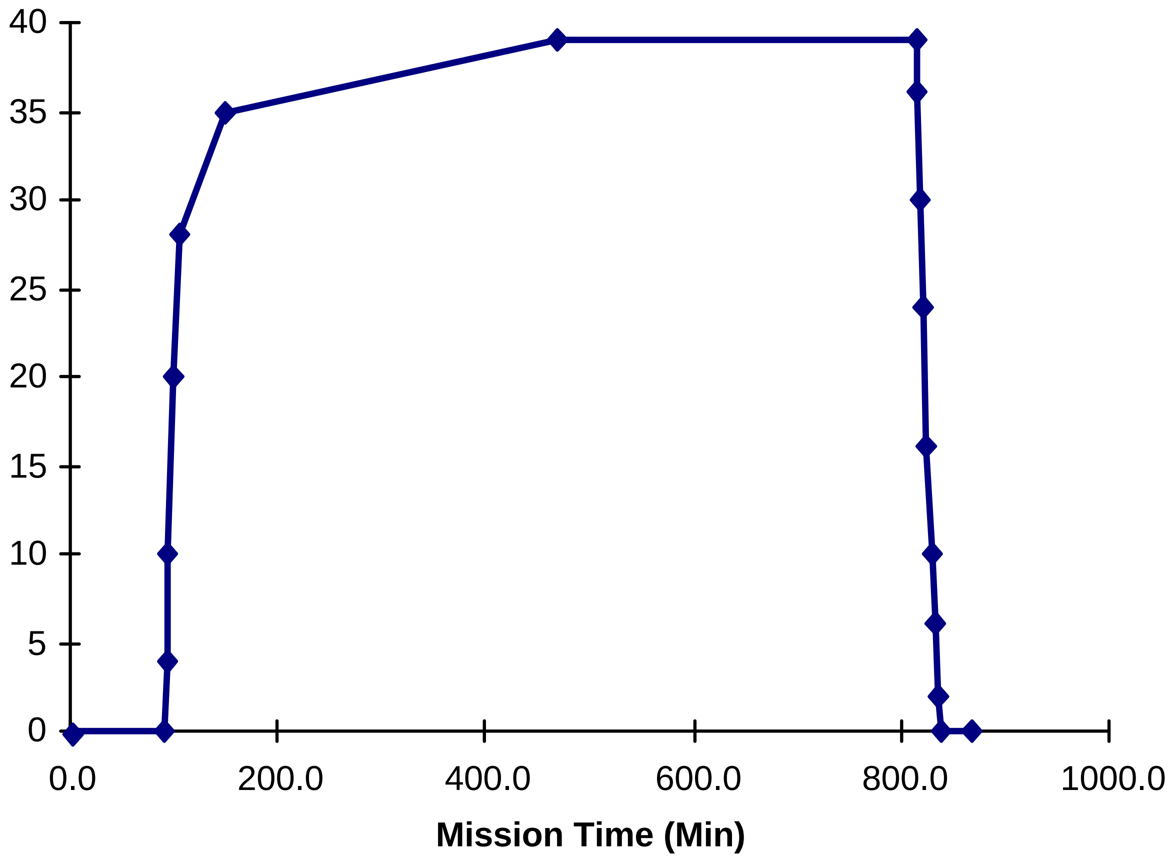


Figure 3.
Aircraft Mission Profile

The other parameters in the analysis can be seen in the tables presented in Appendix A. In summary, this aircraft had a 7363 Ft^3 of fuel tank that was scrubbed for the first 90 minutes if the mission with 2.50 Lbs/min of 4.0 $\%O_2$ NEA . The N_2 flow rate for the rest of the mission was assumed to be 7.0 $\%O_2$ NEA at a flow rate of 0.5 Lbs/min. Also there was 1.0 psi of pressure allowed to build within the fuel tank. The UMacV1 analysis software predicted at these conditions that the oxygen concentration would remain below 9.0 $\%O_2$ in the tank ullage at all times during the mission. The 9.0% level has long been accepted as the maximum level to keep the fuel tank ullage from being able to explode. The maximum flow rate required during the mission was 19.7 Lbs/min which occurred during the descent phase of the mission. See Figures 4 and 5 below for plots of the predicted %O_2 levels in the tank ullage and required NEA flow rate needed to ensure these concentrations.

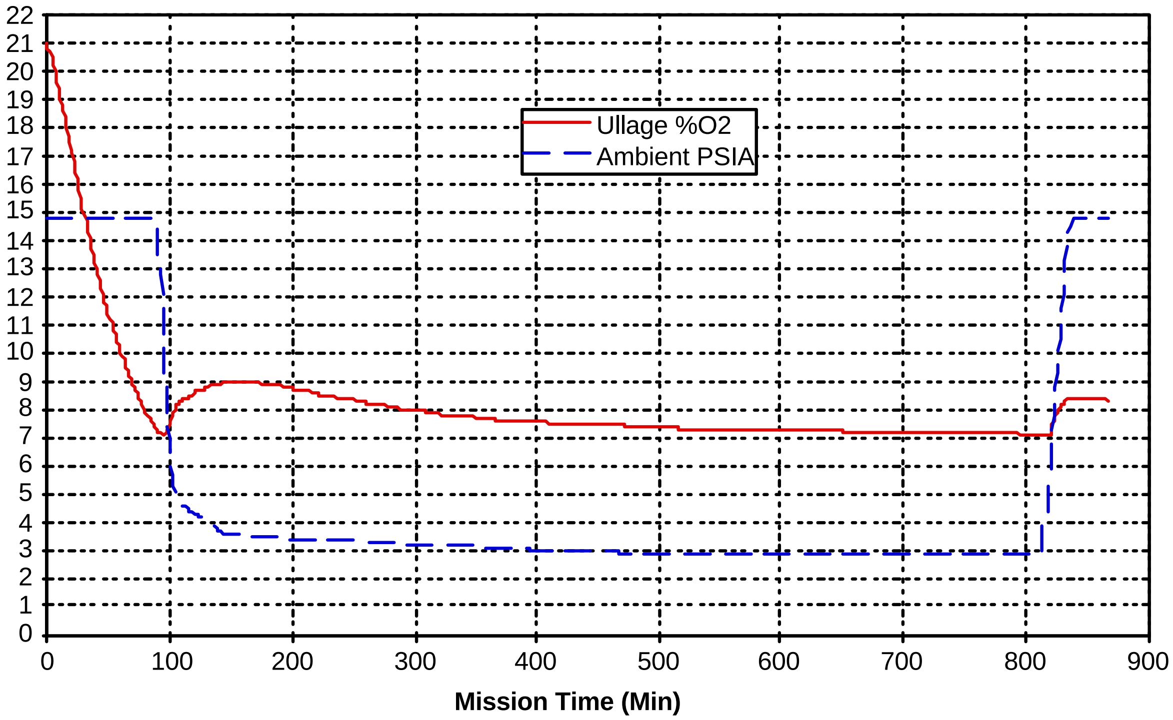


Figure 4.
Predicted %O_2 in Ullage

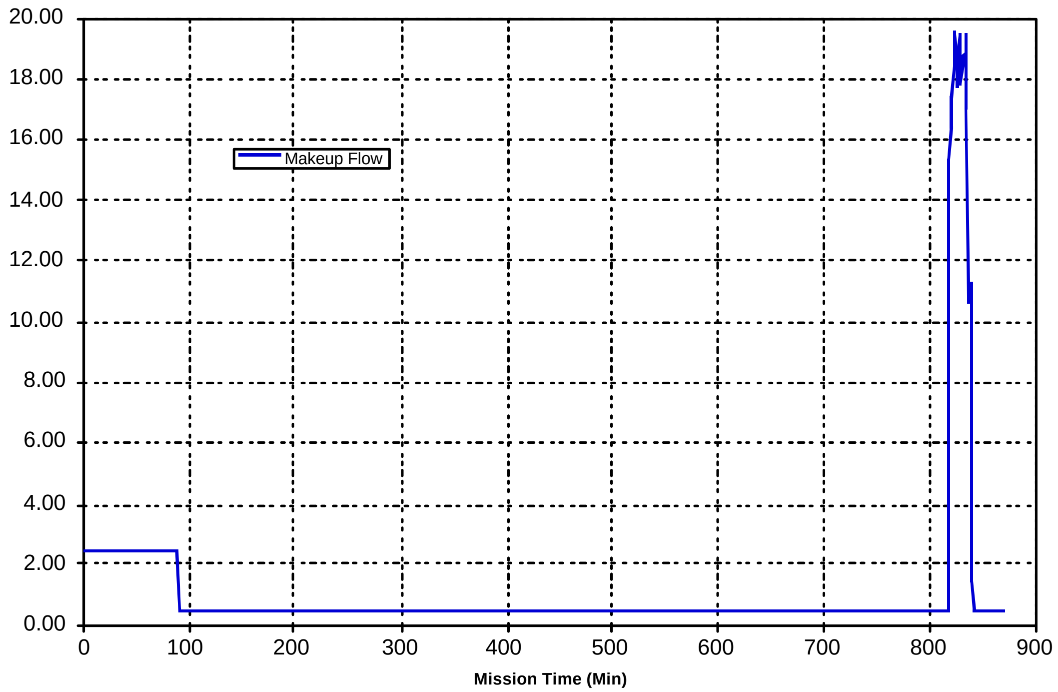


Figure 5.

NEA Flow Rates

Using this software in an iterative fashion allows the trial of numerous different oxygen concentrations, flow rates, etc. to find the configuration that provides the required level of safety. After completing the flow portion of the analysis, the next phase of the analysis is to configure the membrane bundles to provide the required NEA and purity. At this point it's good to note that there are other things that can be done to minimize the size of required OBIGGS on a given. aircraft. Allowing the fuel tanks to become pressurized, that is, minimizing the in-rush of 20.9%O2 air during descent, or by scrubbing the dissolved oxygen from the fuel before it is placed on board the aircraft are two such concepts. While these things can have a significant impact on the size of the aircraft OBIGGS, the focus here is to optimize the system for membranes. The discussions will be centered around taking the required flow rates, and meeting the analysis O_2 concentration requirements, and selecting the proper amount of the correct type of membrane to outfit the aircraft's OBIGGS. Quite often a major portion of configuring OBIGGS is driven around the amount of space available on an aircraft for equipment placement. With this analysis, while maybe impractical, space was assumed to be no object or not a concern. The goal here is to determine the smallest system possible to keep the aircraft inert, as well as use the least amount of engine bleed air during all portions of the mission.

Membrane Selection.

The performance curves shown below are for several different types of membranes at various bleed air pressures. The curves represent the predicted performance levels of fiber bundles, that are the same physical size, but are constructed from several different types of membranes. That is the hollow fiber used in their construction have different permeabilities and selectivities and are representative of what types of membranes are currently available today. The "Standard Composite" performance is (shown by the solid line on the curves) representative of the fiber that has the lowest permeability and the highest selectivity. This simply means that you need more of the "Standard Composite" type of membrane to do a given performance spot than any of the other types of membrane bundles shown on the curve.

The required NEA flow rate for the aircraft during the sustain or fuel make up portion of the mission profile is 0.5 Lbs/min and the required purity is 7.0% O2. The next step to be considered is to determine the available pressure and temperature the Air Separation Module (ASM) will see in operation. The Large commercial transport aircraft as defined by the Fuel Tank Harmonization Working Group has approximately 150 Lbs/min at 41.5 psig_{41K} of engine bleed air at 41,000 Ft Altitude (29.5 psig_{SL}) available for the ECS system including OBIGGS (See Appendix B). For the analysis the OBIGGS feed air temperature is assumed to be 130°F. With this information identified, the bundle selection process can proceed. As shown in Figure 6 below the 0.5 Lbs/min NEA flow rate could be met by incorporating either one of the Asymmetric Non composite ASM's or two of the Standard Composite type, so at first glance it would appear that the Asymmetric Non composite solution would be best. The fact that there is only one module required instead of two makes the weight of the system using the Asymmetric Non composite nearly half the Standard Composite solution. However the Asymmetric Non composite solution will require about 1.8 times the bleed air to make the performance as the Standard Composite ASM's, and this air will be required for the duration of the mission! See Figure 7. This increased feed air flow rate will have an impact on the heat exchanger size and the cooling air requirements as well. The designer of the system has to make a tradeoff between the weight required for the application with two Standard Composite ASM's with their increased weight or one Asymmetric Non composite and the increased inlet air flow.

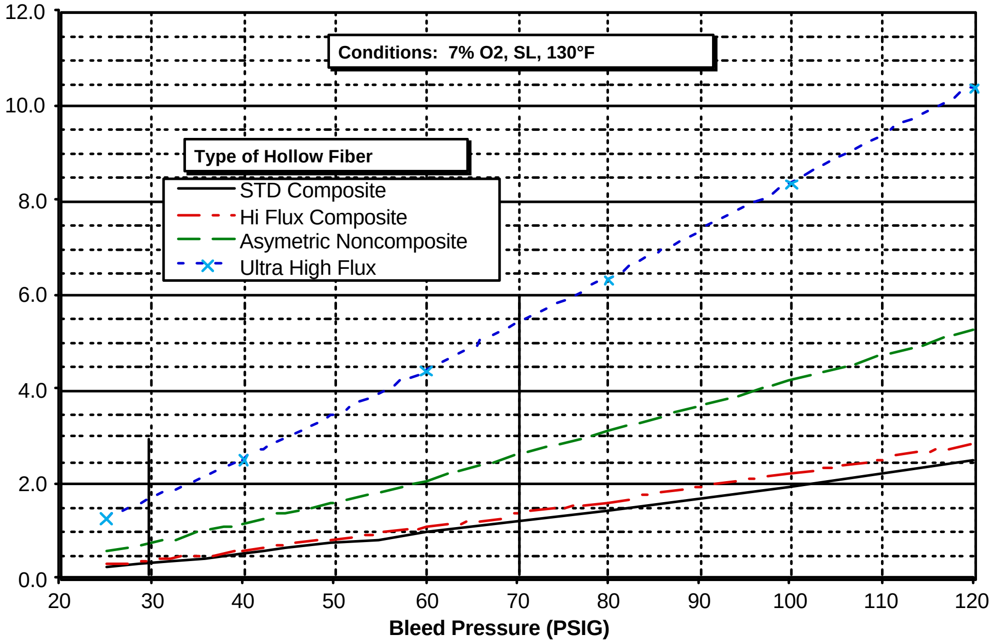


Figure 6.

NEA Flow vs. Feed Pressure

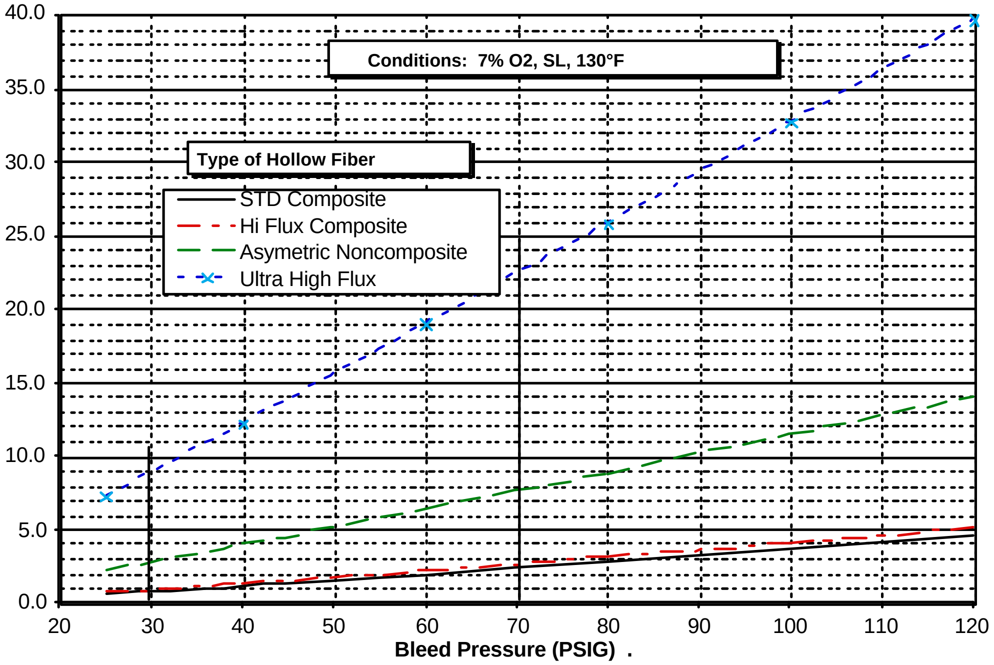


Figure 7.

ASM Feed Flow vs. Feed Pressure

A similar type of analysis can be done for each of the remaining phases of the flight. The portion of the flight that will have the highest impact on the aircraft systems is the descent, that is, the trade off's that a system designer would have to make become more significant for this portion of the system. The required flow rate for the descent as determined by the fuel tank analysis is 19.7 Lbs/min and the required purity of the NEA is 9.% O2 . Using the Standard Composite and the Ultra High Flux ASM's for this part of the analysis, the choices become either 10 modules required at 85 Lbs/min verses 64 module requiring 25 Lbs/min of fed air. To completely optimize this aircraft's OBIGGS, clearly a higher source of pressure is required due the ASM's performance having a strong dependence on pressure. If the pressure in the system were to be 70 psig, then the number of modules can be reduced down to 2 at 64 Lbs/min for the Ultra High Flux ASM's and 12 at 35 Lbs/min for the Standard Composite ASM's. The source of pressure does not have to be the engine bleed air for the descent phase of the flight because it is only required for a short portion of the entire mission. An auxiliary compressor could be used for this task, again the system designer will have to do a benefit analysis for the specific application to see which is best suited for the application. To further highlight the importance of feed pressure, at the end of Appendix C there are curves that show the weight of the ASM's required based on the feed pressure available. This data clearly shows how critical feed pressure is to OBIGGS that uses Hollow Fiber Permeable Membranes to create NEA from compressed air.

Appendix A
Fuel Tank Analysis - Input Data

ITYPE 1=JP4 2=JP5/Jet A 3=JP8	RVP (psi)
2	1.95

PreScrub ? (Y/N)	O2 Fraction (0 - 0.209) (ULLOX)
n	0.05

Scrub During ? (Y/N)	Phase 1 O2 Frac (0 - 0.209)	Phase 1 Flow (Lbs/Min)	Phase 1 Duration (Min)	Efficiency (0 - 1)	Phase 2 O2 Frac (0 - 0.209)	Phase 2 Flow (Lbs/Min)
y	0.04	2.5	90	0.95	0.07	0.5

Vent MakeUp O2 Fraction (0 - 0.209)
0.09

Tank Vol (Ft3)	Area (Ft2)	Demand Reg (psig)	Climb Valve (psig)
7363	2945	0	1

Mission Time (Min)	Ullage Vol (Ft3)	Altitiude (KFt or psia)	Tfuel (F or R)	Ttop skin (F or R)	Ullage Fraction
0.0	488.3	0	37.4	35.4	0.066
90.0	506.8	0	37.4	35.4	0.069
93.1	588.9	4	47.9	45.9	0.080
95.2	639.5	10	38.8	36.8	0.087
100.3	751.6	20	44.4	42.4	0.102
105.3	842.4	28	26.6	24.6	0.114
148.8	1300.6	35	-2.0	-4.0	0.177
469.2	4112.4	39	-6.5	-8.5	0.559
813.8	6570.3	39	-6.5	-8.5	0.892
814.8	6571.3	36	-7.8	-9.8	0.892
817.5	6574.3	30	4.1	2.1	0.893
820.3	6577.8	24	17.6	15.6	0.893
824.4	6583.9	16	32.0	30.0	0.894
828.5	6591.2	10	35.0	33.0	0.895
831.47	6597.252	6	41.396	39.4	0.896
834.632	6603.751	2	48.125	46.1	0.897
839.034	6621.047	0	37.4	35.4	0.899
869.034	6631.33	0	37.4	35.4	0.901

```
******  FUEL PROPERTIES  ******

  497.4   INITIAL FUEL TEMP - DEG R
  0.004   INITIAL VAPOR PRESSURE-PSI
  0.198   INITIAL OSTWALD COEFF. O2
  0.098   INITIAL OSTWALD COEFF. N2
                     "

***********GIVEN CONDITIONS*************

   7363   TANK VOLUME (FT^3)
   2945   FUEL SURFACE AREA (FT^2)
      9   VENT MAKEUP GAS (O2 VOL%)
      0   DEMAND REG. SETTING (PSID)
      1   CLIMB VALVE SETTING (PSIC
    2.5          0.5   Phase 1 & 2 SCRUB FLOWRATE (LB/MIN)
      4            7   Phase 1 & 2 SCRUB O2 CONC. (O2 VOL%)
   0.95   SCRUB EFFICIENCY
     90   LENGTH OF SCRUB (MIN)


********* CONDITIONS*************

  9.005   ULLAGE O2 MASS (LBS)
  29.84   ULLAGE N2 MASS (LBS)
  3.072   ULLAGE PP O2 (PSIA)
  25.09   DISSOLVED O2 MASS (LBS)
```

Appendix B

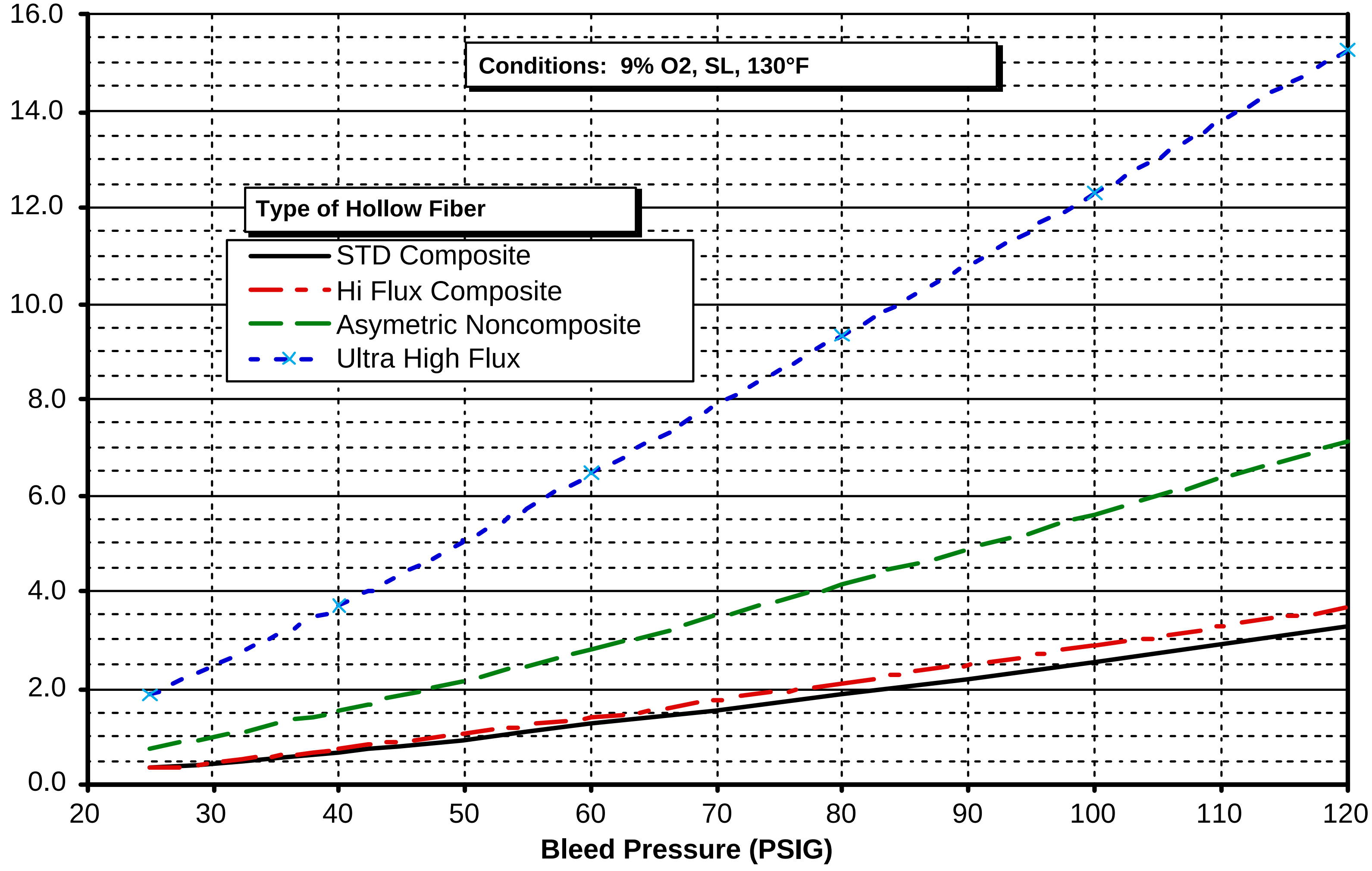
Engine Bleed Air Data

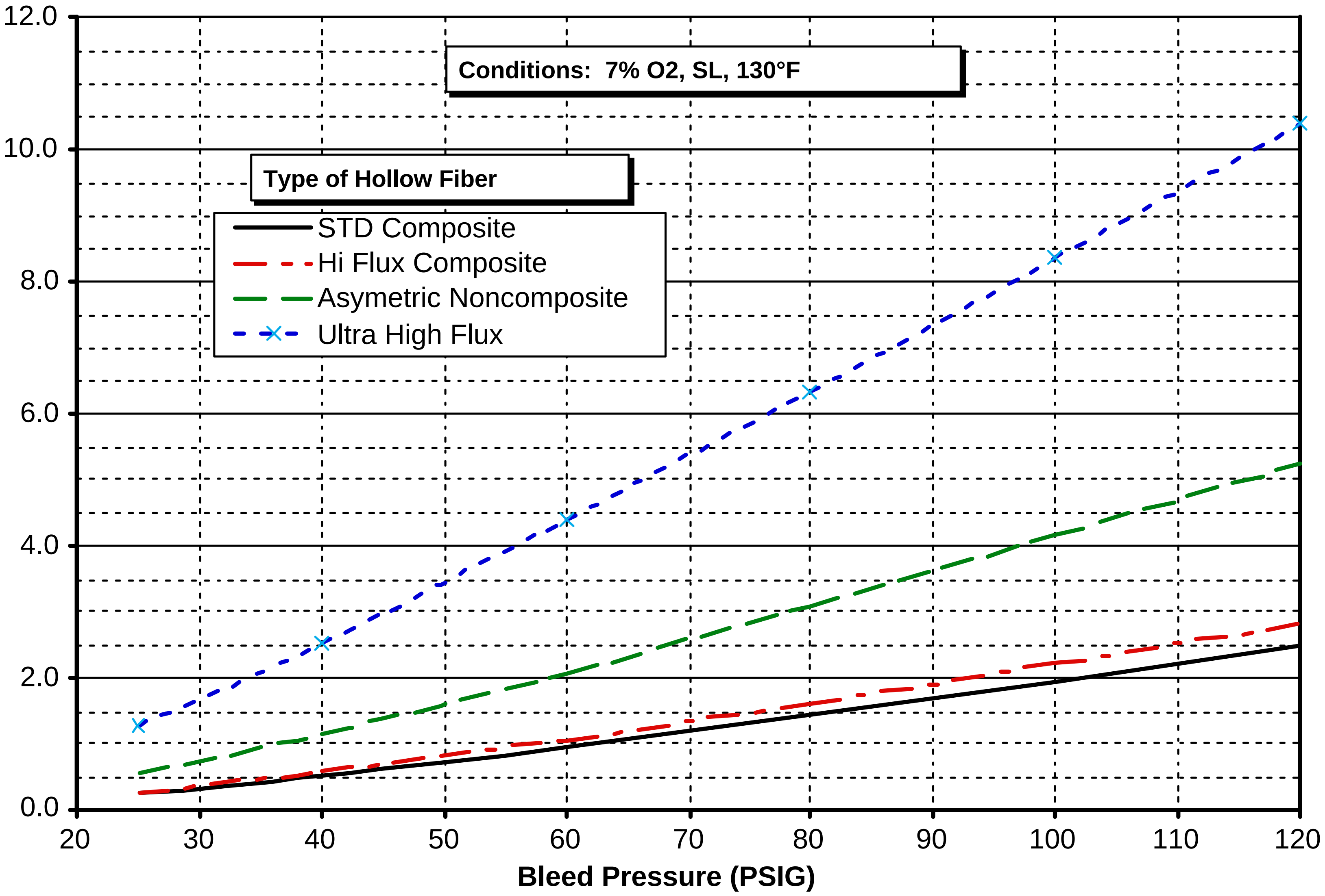
Large Transport Bleed Performance

Anti-ice Off			
Altitude (ft)	Bleed		Condition
	Pressure (psig)	Flow (lbs/min)	
43000	18.2	150	Minimum Idle
40000	18.9	150	Minimum Idle
35000	20.2	150	Minimum Idle
31000	22.9	150	Minimum Idle
25000	22.4	150	Minimum Idle
20000	24	150	Minimum Idle
15000	25.6	150	Minimum Idle
10000	27.1	150	Minimum Idle
5000	28.8	150	Minimum Idle
0	29.8	150	Minimum Idle
40000	41.5	150	Cruise
35000	35.8	150	Cruise
31000	28	150	Cruise
0	29.8	4	Ground Idle
0	29.8	4	Climb

Appendix C

ASM Performance Curves


Conditions: 9% O2, SL, 130°F
Type of Hollow Fiber
STD Composite
Hi Flux Composite
Asymetric Noncomposite
Ultra High Flux
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
20
30
40
50
60
70
80
90
100
110
120
Bleed Pressure (PSIG)


Conditions: 7% O2, SL, 130°F
Type of Hollow Fiber
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Hi Flux Composite
Asymetric Noncomposite
Ultra High Flux
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10.0
8.0
6.0
4.0
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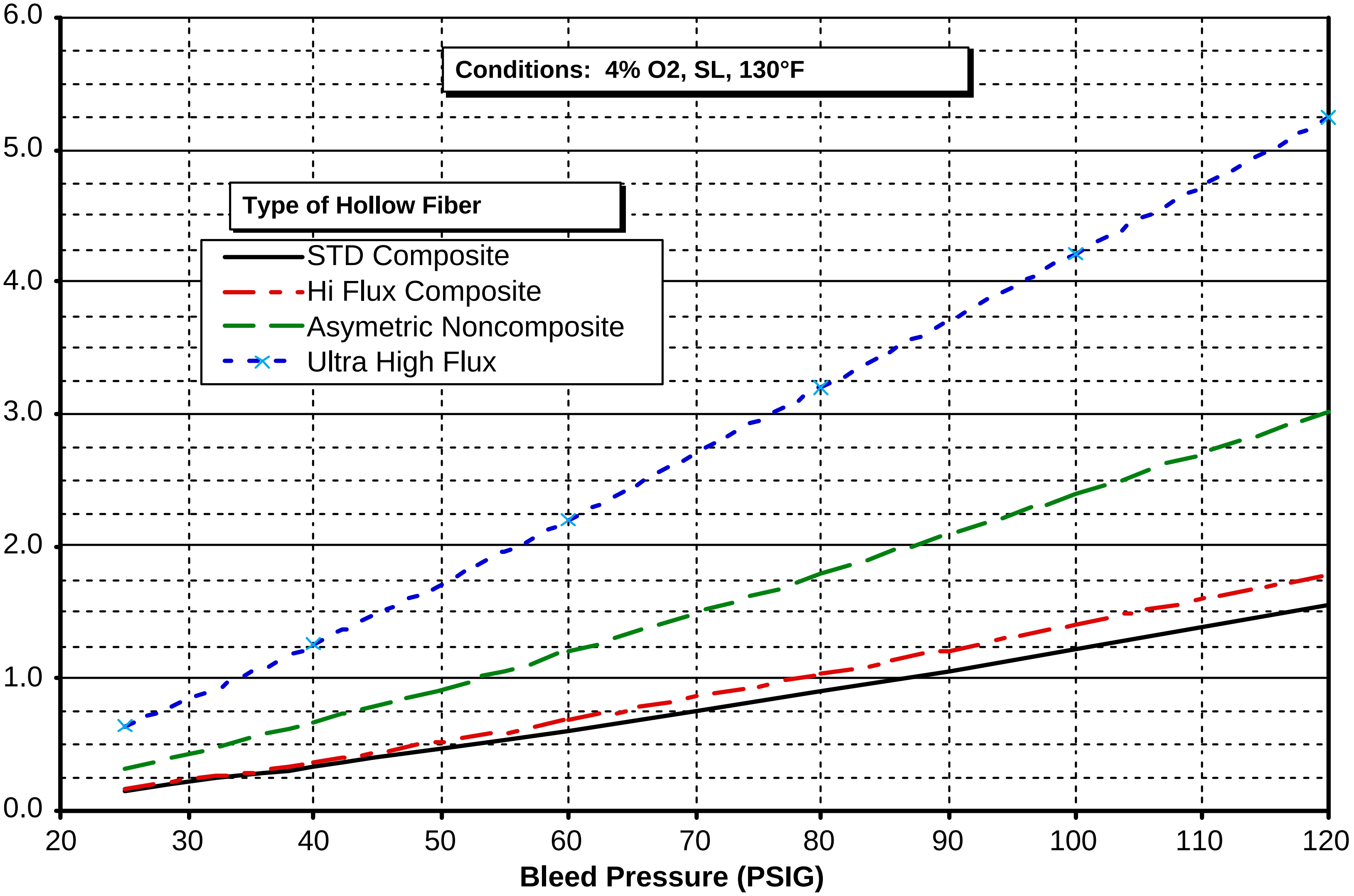
Bleed Pressure (PSIG)


Conditions: 4% O2, SL, 130°F
Type of Hollow Fiber
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Hi Flux Composite
Asymetric Noncomposite
Ultra High Flux
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5.0
4.0
3.0
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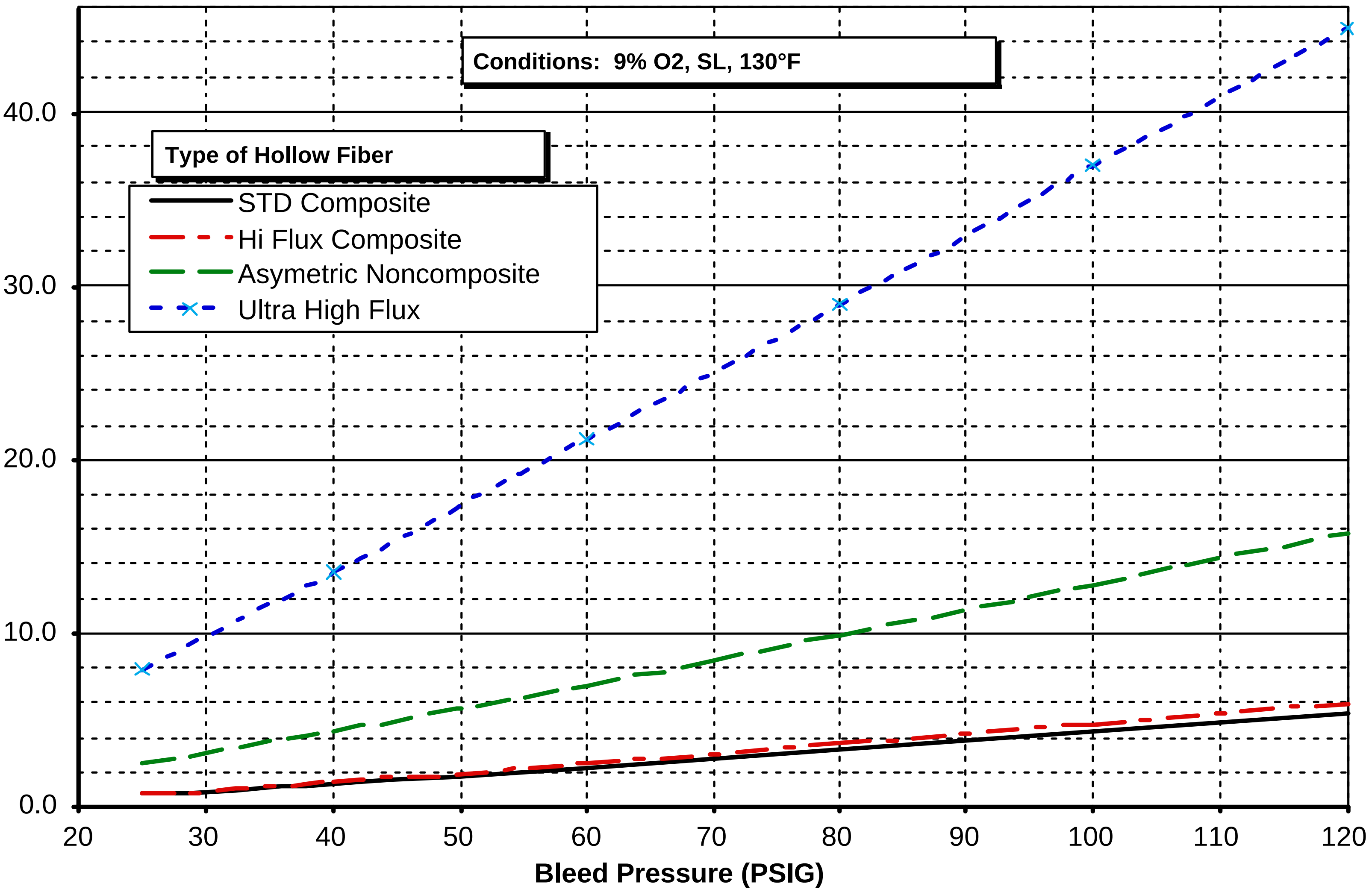
Bleed Pressure (PSIG)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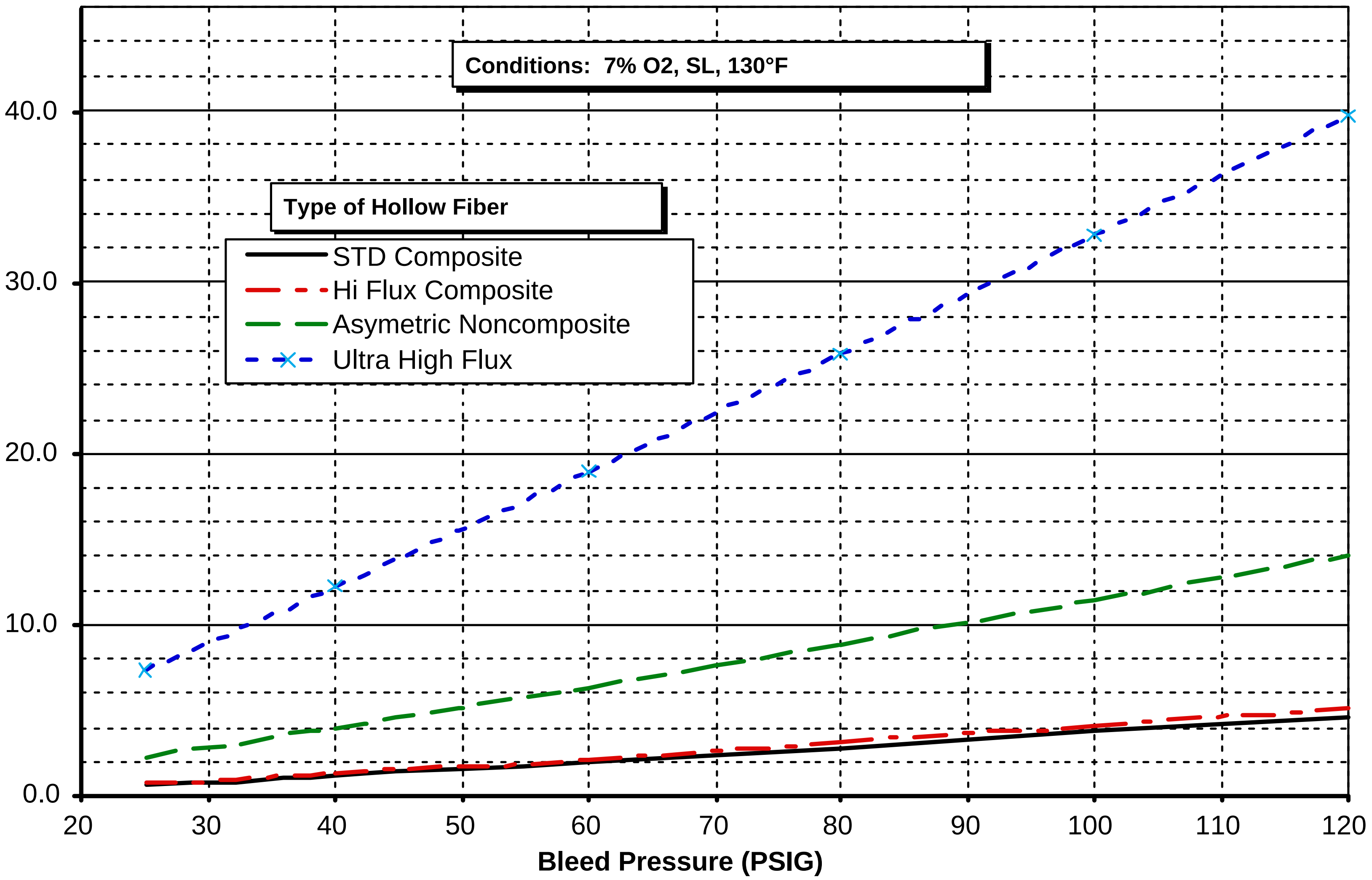
Bleed Pressure (PSIG)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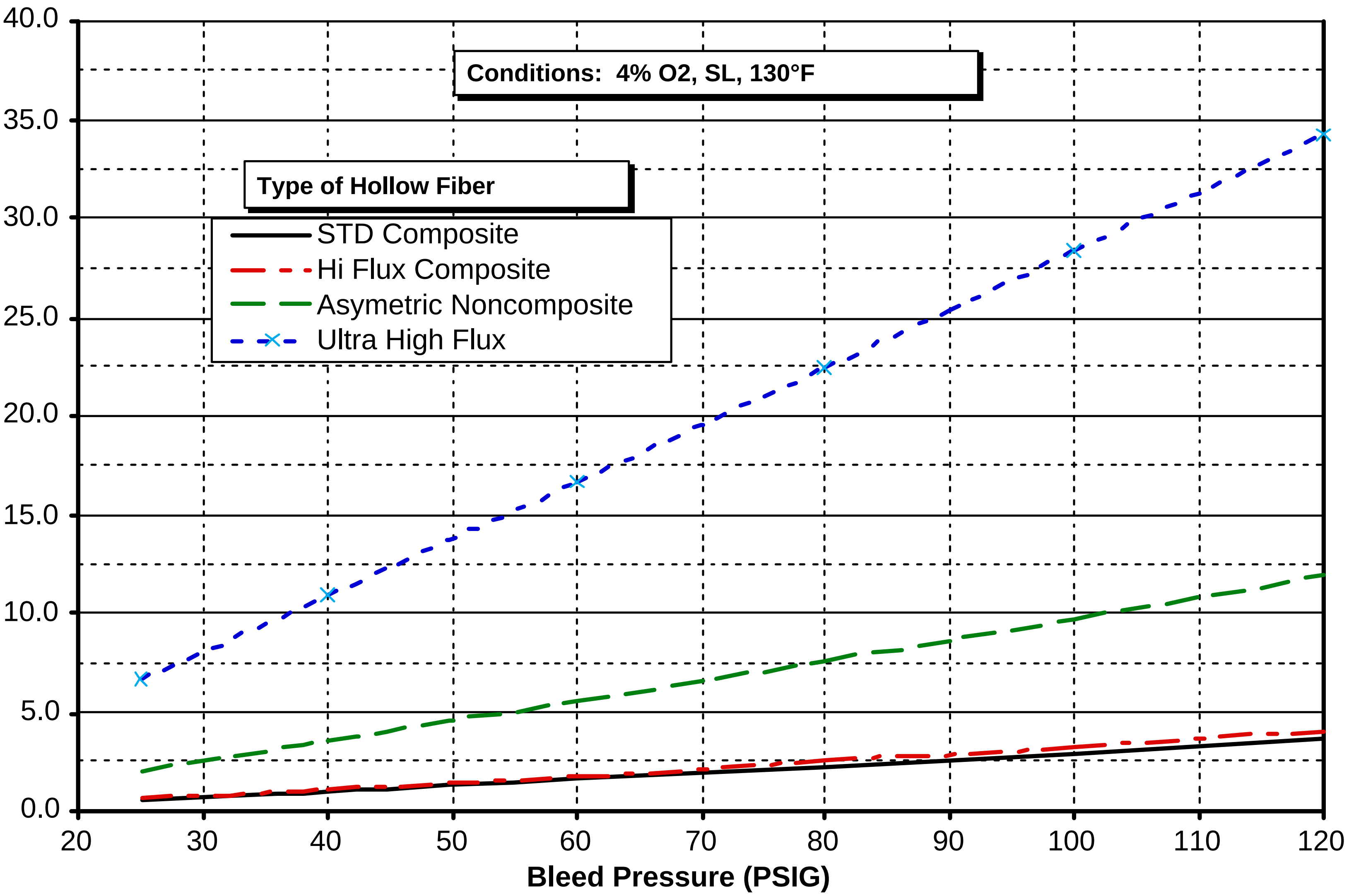
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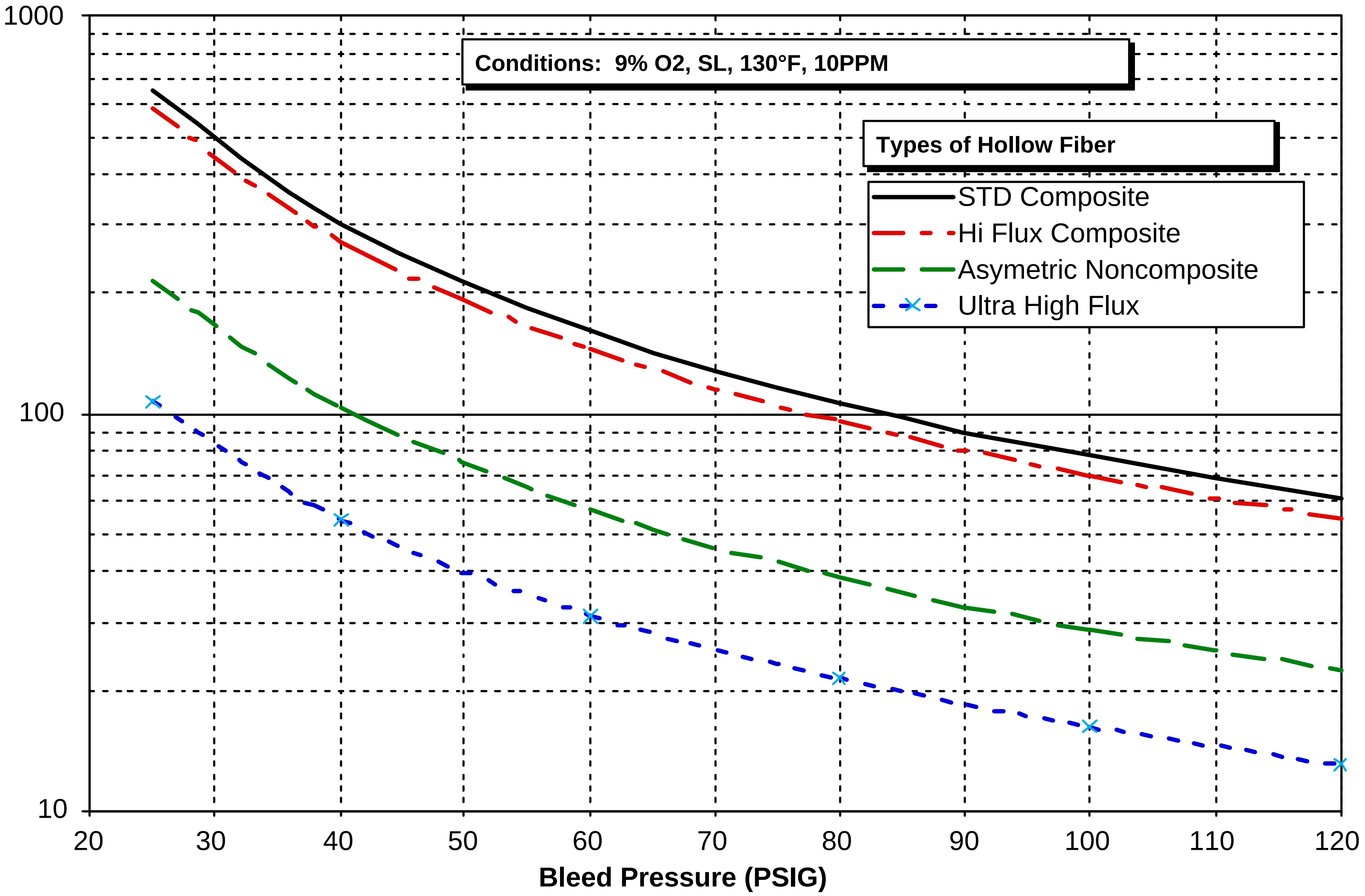
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Asymetric Noncomposite
Ultra High Flux
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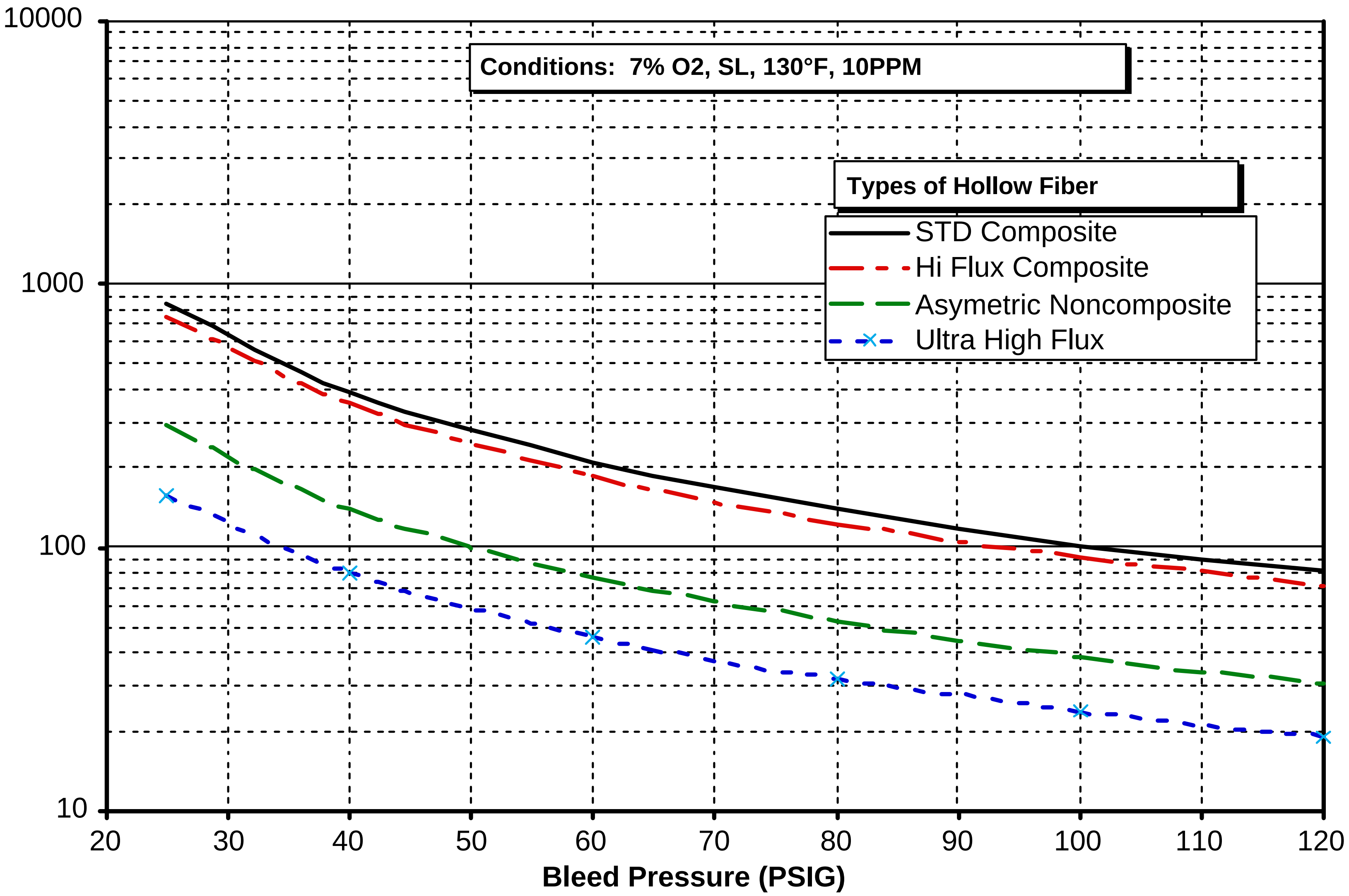
Bleed Pressure (PSIG)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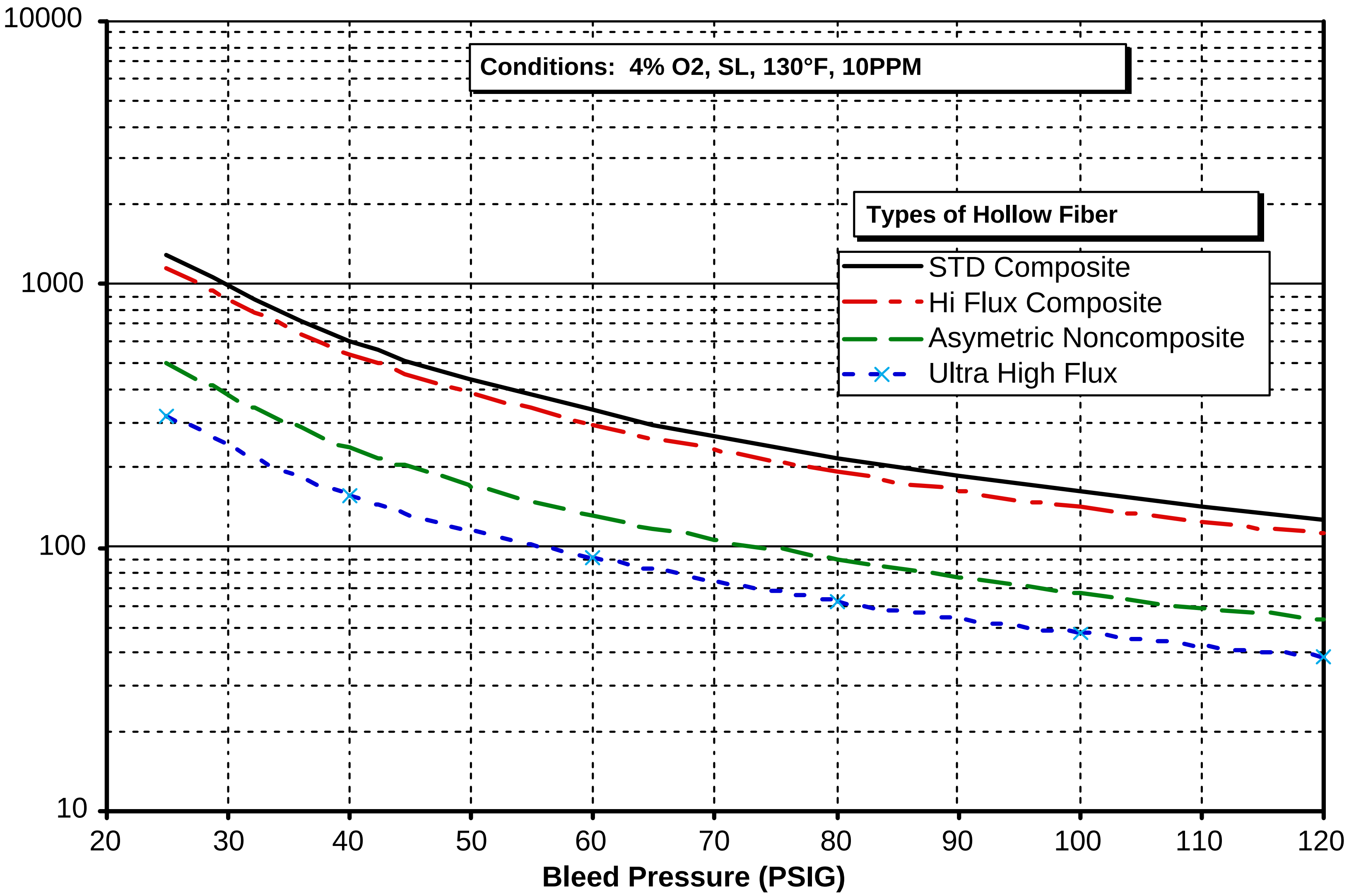
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