3
BDX-613-1033

DESIGN MANUAL FOR POLYSTYRENE FOAM,
RELATING PHYSICAL, MECHANICAL,
AND CHEMICAL PROPERTIES

Prepared by:
D. J. Fossey
Department 814

Internal Distribution February 1974

MASTER

Prepared for the
United States Atomic Energy Commission
Under Contract Number AT(29-1)-613 USAEC

**Kansas City
Division**

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DESIGN MANUAL FOR POLYSTYRENE FOAM,
RELATING PHYSICAL, MECHANICAL,
AND CHEMICAL PROPERTIES

BDX-613-1033

Internal Distribution February 1974

Prepared by:
D. J. Fossey
Department 814

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Technical Communications

**Kansas City
Division**

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

**DESIGN MANUAL FOR POLYSTYRENE FOAM RELATING PHYSICAL, MECHANICAL,
AND CHEMICAL PROPERTIES**

**BDX-613-1033, UNCLASSIFIED Design Manual, Internal Distribution
February 1974**

Prepared by D. J. Fossey, D/814

A process has been developed at Bendix Kansas City to mold large cylinders of a high quality polymer. The process involves pre-expansion of expandable polystyrene beads to the desirable bulk density and molding the expanded beads into large cylinders using nitrogen to heat the beads in an autoclave to approximately 210°F (99°C). After molding, the foam cylinders are then machined into the desired shapes. The physical, mechanical, and chemical properties of the polystyrene bead foam are characterized in this document by a collection of tables and graphs.

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

THE BENDIX CORPORATION

KANSAS CITY DIVISION

KANSAS CITY, MISSOURI

A prime contractor for the
Atomic Energy Commission
Contract Number AT(29-1)-613 USAEC

CONTENTS

Section	Page
INTRODUCTION	7
1 TYPICAL PHYSICAL, MECHANICAL, AND CHEMICAL PROPERTIES.	9
2 MASTER CURVES RELATING MECHANICAL PROPERTIES TO TEMPERATURE AND STRAIN RATE	17
3 MECHANICAL PROPERTIES AS A FUNCTION OF STRAIN RATE . . .	25
4 MECHANICAL PROPERTIES AS A FUNCTION OF TEMPERATURE . . .	28
5 MECHANICAL PROPERTIES AS A FUNCTION OF DENSITY	35
6 MECHANICAL PROPERTIES AS A FUNCTION OF n-PENTANE CONTENT	41
7 TYPICAL STRESS-STRAIN CURVES	44
8 MISCELLANEOUS GRAPHS	48
9 BIBLIOGRAPHY	53

ILLUSTRATIONS

Figure		Page
1	Master Curves for 50 kg/m ³ PSBF in Compression . . .	18
2	Master Curves for 50 kg/m ³ PSBF in Tension	19
3	Master Curves for 100 kg/m ³ PSBF in Compression	20
4	Master Curves for 100 kg/m ³ PSBF in Tension.	21
5	Master Curves for Solid Polystyrene Resin in Compression	22
6	Master Curves for Solid Polystyrene Resin in Tension	23
7	Master Curves for the Dynamic Shear Modulus of Three PSBF and Solid Resin.	24
8	Yield Stress Versus Strain Rate at 73°F (23°C) for PSBF and Solid Resin.	26
9	Modulus Versus Strain Rate at 73°F (23°C) for PSBF and Solid Resin.	27
10	Tensile Stress at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin	29
11	Compressive Stress at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin.	30
12	Modulus Versus Temperature for PSBF and Solid Polystyrene Resin	31
13	Tensile Strain at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin.	32
14	Compressive Strain at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin.	33
15	Dynamic Shear Modulus of 50 kg/m ³ PSBF at Various Temperatures and Testing Frequencies. . . .	34

16	Tensile Yield Stress Versus Density.	36
17	Compressive Yield Stress Versus Density.	37
18	Tensile Modulus Versus Density	38
19	Compressive Modulus Versus Density	39
20	Dynamic Shear Modulus of PSBF as a Function of Density.	40
21	Theoretical Glass Transition Temperature of PSBF and Solid Polystyrene Resin Versus n-Pentane Content	42
22	Ultimate Tensile Stress of PSBF Versus n-Pentane Content	43
23	Typical Stress-Strain Curves for 50 kg/m ³ PSBF at Various Temperatures.	45
24	Typical Stress-Strain Curves for 100 kg/m ³ PSBF at Various Temperatures.	46
25	Typical Stress-Strain Curves for Solid 1040 kg/m ³ Polystyrene Resin at Various Temperatures.	47
26	Equilibrium Moisture Content of PSBF	49
27	Percent of Total n-Pentane Content in Vapor Phase of PSBF	50
28	Vapor Pressure of n-Pentane in PSBF.	51
29	Activity of n-Pentane in PSBF.	52

TABLES

Number		Page
1	Typical Mechanical Properties of KFP-572 PSBF at Room Temperature.	10
2	Typical Chemical Analysis of KFP-572 PSBF	11
3	Typical Physical Properties of KFP-572 PSBF	12
4	Theoretical Diffusivity Values (cm^2/s) for Gases Through KFP-572 PSBF	13
5	Experimental Diffusivity of n-Pentane as a Function of Average Concentration.	14
6	Experimental Diffusivity Equations for n-Pentane Through KFP-572 PSBF as a Function of Temperature.	15
7	Definition of Symbols	16

INTRODUCTION

The physical, mechanical, and chemical properties of polystyrene bead foam (PSBF) are characterized in this document by a collection of tables and graphs. Sinclair-Koppers' KFP-572 expandable polystyrene beads were used. The data were obtained from 50 kg/m³ and 100 kg/m³ cylindrical foam blocks 42 inches (1.067 m) in diameter and 29 inches (0.737 m) high. Data from Dow Chemical's SD-606 solid feedstock are also included.

A process has been developed at Bendix Kansas City to mold large cylinders of high quality polymers. The process involves pre-expansion of the expandable polystyrene beads to the desirable bulk density and molding the expanded beads into large cylinders using nitrogen to heat the beads in an autoclave to approximately 210°F (99°C). After molding, the foam cylinders are then machined into the desired shapes.

Section 1 contains tables of typical values for the physical, mechanical, and chemical properties of 50 kg/m³ and 100 kg/m³ foams that have been produced at Bendix. Section 2 contains master curves that relate the mechanical properties to the two test parameters, temperature and strain rate. This relationship is shown by plotting the logarithm of the mechanical property against the logarithm of the reduced strain rate. The reduced strain rate, E_R , takes into account the testing variables of temperature and strain rate, E_A , using the following equations.

$$E_R = E_A a_T \text{ and} \quad (1)$$

$$\log a_T = \frac{\Delta H}{2.3R} \left(\frac{1}{T} - \frac{1}{T_0} \right) \quad (2)$$

Where:

E_R = the reduced strain rate,

E_A = the test strain rate,

a_T = the shift factor,

ΔH = the activation energy, kcal/mole

R = the universal gas constant, 1.987 cal/mole K,

T_0 = the reference temperature, K, and

T = the test temperature, K.

The values of T_0 and ΔH used for the master curves were 296K (23°C) and 44 kcal/mol, respectively.

Sections 3 through 6 contain graphs relating testing and material variables to the mechanical properties. Section 7 has typical stress-strain curves for the foam and solid resin. Section 8 contains miscellaneous graphs. An extensive reference bibliography on the molding, testing, and properties of KFP-572 polystyrene foam is found in Section 9.

Most of the tables and graphs contained in this report have been previously presented in the reports listed in the bibliography.

Section 1

**TYPICAL PHYSICAL, MECHANICAL,
AND CHEMICAL PROPERTIES**

Table 1. Typical Mechanical Properties of KFP-572 PSBF at Room Temperature

Property	Foam Density	
	(50 kg/m ³)	(100 kg/m ³)
Ultimate Tensile Strength*	75 to 110 psi (517 to 758 kPa)	160 to 200 psi (1103 to 1379 kPa)
Compressive Yield Strength*	45 to 55 psi (310 to 379 kPa)	120 to 180 psi (827 to 1241 kPa)
Tensile Modulus*	4.8 to 6.3 kpsi (33.1 to 43.4 MPa)	10.5 to 13.5 kpsi (72.4 to 93.1 MPa)
Compressive Modulus*	4.3 to 5.2 kpsi (29.6 to 35.8 MPa)	9.3 to 11.8 kpsi (64.1 to 81.4 MPa)
Shear Modulus*	2.1 kpsi (14.5 MPa)	4.3 kpsi (29.6 MPa)
Poisson Ratio (Tension)**	0.31	0.33
Poisson Ratio (Compression)**	0.21	0.25
Coefficient of Linear Thermal Expansion***	35 to 45 $\mu\text{in./in.}\cdot^{\circ}\text{F}$ (63 to 81 $\mu\text{m/m}\cdot^{\circ}\text{C}$)	35 to 45 $\mu\text{in./in.}\cdot^{\circ}\text{F}$ (63 to 81 $\mu\text{m/m}\cdot^{\circ}\text{C}$)
Thermal Conductivity†	0.215 (Btu·in./Ft ² ·Hr·°F) (0.030 w/m·K)	0.216 (Btu·in./Ft ² ·Hr·°F) (0.031 w/m·K)
Heat Distortion Temperature††	~180°F (82°C)	~180°F (82°C)
<p>*Mechanical properties vary with n-pentane content. Values are based on material containing 1 to 2 percent n-pentane. See Section 6, Figure 22.</p> <p>**On SD-505 Polystyrene Bead Foam; this expandable polystyrene bead material was used in early stages of process development work.</p> <p>***Varies with temperature.</p> <p>†In accordance with ASTM-C-177-63</p> <p>††Varies with n-pentane content; see Figure 21, Section 6.</p>		

Table 2. Typical Chemical Analysis of KFP-572 PSBF

Property	Value
Elemental Analysis	
Carbon	92 Percent
Hydrogen	8 Percent
Chlorine	1 to 50 ppm
Bromine	Less than 1 ppm
Iodine	Less than 0.1 ppm
Zinc	4 to 30 ppm
Volatile Content	3.5 to 5.5 Percent
Moisture Content	Less than 0.02 Percent*
Ash Content	10 to 50 ppm
Molecular Weight	
$\bar{M}_w$	260,000 to 320,000
$\bar{M}_n$	80,000 to 122,000
$\bar{M}_w/\bar{M}_n$	2.1 to 3.5
*Varies with relative humidity; see Figure 26, Section 8	

Table 3. Typical Physical Properties of KFP-572 PSBF

Property	Foam Density	
	(50 kg/m ³)	(100 kg/m ³)
Density Uniformity*	±10 Percent	±10 Percent
Voids**	None	None
Cell Diameter	450 µm	100 µm
Cell Wall Thickness	3 µm	1 µm
Surface Finish	11.4 µm	7.6 µm
Machineability	Good	Good
Bonding Compatibility	Good	Good
Dimensional Stability***	<0.005 inch (12.70 mm) shrinkage in 230 days	<0.005 inch (12.70 mm) shrinkage in 230 days
<p>*Molded according to Bendix Processing Engineering Specification P1251037</p> <p>**Meets requirements of RM 253470 paragraph 3.2.2</p> <p>***After a seven week stabilization cycle at 170°F (88.7°C)</p>		

Table 4. Theoretical Diffusivity Values (cm^2/s) for Gases Through KFP-572 PSBP

Gas	Temperature		Density		Concentration Weight Fraction (g/g)
	(°F)	(°C)	(50 kg/m^3)	(100 kg/m^3)	
n-Pentane	77	(25)	1.2×10^{-8}	3.9×10^{-9}	0.021
	77	(25)	3.7×10^{-8}	1.2×10^{-8}	0.054
	167	(75)	2.5×10^{-8}	9.5×10^{-8}	0.009
	167	(75)	5.8×10^{-8}	2.2×10^{-8}	0.019
Nitrogen*	77	(25)	2.6×10^{-7}	1.1×10^{-7}	
	122	(50)	5.7×10^{-7}	2.5×10^{-7}	
	167	(75)	1.2×10^{-6}	5.0×10^{-7}	
Oxygen*	77	(25)	2.3×10^{-6}	7.6×10^{-7}	
	122	(50)	4.1×10^{-6}	1.7×10^{-6}	
	167	(75)	6.7×10^{-6}	2.8×10^{-6}	
Water*	77	(25)	7.8×10^{-4}	2.6×10^{-4}	
	158	(70)	1.1×10^{-3}	4.5×10^{-4}	
Nitrogen* At 50 kg/m^3 , $D = 9.13 \times 10^{-3} \exp(-6205/RT)**$ At 100 kg/m^3 , $D = 3.15 \times 10^{-3} \exp(-6132/RT)$					
Oxygen* At 50 kg/m^3 , $D = 3.68 \times 10^{-3} \exp(-4329/RT)$ At 100 kg/m^3 , $D = 5.99 \times 10^{-3} \exp(-5381/RT)$					
*Independent of concentration **R = 1.987 calories per mole per Kelvin					

Table 5. Experimental Diffusivity of n-Pentane as a Function of Average Concentration

Temperature (°F) (°C)	Polystyrene Bead Foam Density (50 kg/m ³)	
	Equation for $D=D(C)^*$ (cm ² /sec)	Range of Con- centration Weight Fraction (g/g)
77 (25)	$D = 5.0 \times 10^{-8}$	All
120 (49)	$D = 2.5 \times 10^{-7}$	$C_t > 0.011$
	$D = 2.0 \times 10^{-8}$	$C_t < 0.011$
150 (66)	$D = 4.0 \times 10^{-7}$	$C_t > 0.010$
	$D = 1.5 \times 10^{-7} + 2.5 C_t \times 10^{-5}$	$C_t < 0.010$
170 (77)	$D = 6.2 \times 10^{-7}$	$C_t > 0.010$
	$D = 2.3 \times 10^{-7} + 3.9 C_t \times 10^{-5}$	$C_t < 0.010$
Polystyrene Bead Foam Density (100 kg/m ³)		
77 (25)	$D = 2 \times 10^{-8}$	All
120 (49)	$D = 7 \times 10^{-8}$	All
150 (66)	$D = 1.3 \times 10^{-7}$	$C_t > 0.011$
	$D = 5 \times 10^{-8} + 7.3 C_t \times 10^{-6}$	$C_t < 0.011$
170 (77)	$D = 3.1 \times 10^{-7}$	$C_t > 0.009$
	$D = 2.1 \times 10^{-7} + 1.1 C_t \times 10^{-5}$	$C_t < 0.009$
*Diffusivity as a function of concentration.		

Table 6. Experimental Diffusivity Equations for n-Pentane Through KFP-572 PSBF as a Function of Temperature

Foam Density (kg/m ³)	n-Pentane Concentration (Percent)	Arrhenius Equation $D = D_0 \exp (-E/RT)^*$
50	>1.0	$D = 2.39 \exp (-9500/RT)$
50	0.5	$D = 1.98 \exp (-9650/RT)$
50	0.25	$D = 13.5 \exp (-11,000/RT)$
50	0.0	$D = 48,900 \exp (-16,360/RT)$
100	>1.0	$D = 1.25 \exp (-10,040/RT)$
100	0.5	$D = 5.2 \times 10^8 \exp (-22,170/RT)$
100	0.25	$D = 1.5 \times 10^{11} \exp (-25,830/RT)$
100	0.0	$D = 4.7 \times 10^{13} \exp (-29,520/RT)$
*D = Diffusivity, cm ² /s, R = 1.987 calories per mole per Kelvin, and T = Temperature in R.		

Table 7. Definition of Symbols

Symbol	Definition
E_T	Reduced strain rate
E_A	Strain rate used in actual test
a_T	Shift factor
ΔH	Activation energy
R	Universal gas constant
T	Test temperature
T_0	Reference temperature
$\bar{M}_w$	Weight-average molecular weight
$\bar{M}_n$	Number-average molecular weight
D	Diffusivity
C_t	Concentration of n-pentane in the foam at time
P	Partial vapor pressure
P_0	Total vapor pressure

Section 2

MASTER CURVES RELATING
MECHANICAL PROPERTIES
TO TEMPERATURE AND
STRAIN RATE

Figure 1. Master Curves for 50 kg/m³ PSBF in Compression

Figure 2. Master Curves for 50 kg/m³ PSBF in Tension

Figure 3. Master Curves for 100 kg/m³ PSBF in Compression

Figure 4. Master Curves for 100 kg/m³ PSBF in Tension

Figure 5. Master Curves for Solid Polystyrene Resin in Compression

Figure 6. Master Curves for Solid Polystyrene Resin in Tension

Figure 7. Master Curves for the Dynamic Shear Modulus of Three PSBF and Solid Resin

Section 3

MECHANICAL PROPERTIES AS A FUNCTION OF STRAIN RATE

Figure 8. Yield Stress Versus Strain Rate at 73°F (23°C) for PSBF and Solid Resin

Figure 9. Modulus Versus Strain Rate at 73°F (23°C) for PSBF and Solid Resin

Section 4

MECHANICAL PROPERTIES AS A
FUNCTION OF TEMPERATURE

Figure 10. Tensile Stress at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin

Figure 11. Compressive Stress at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin

Figure 12. Modulus Versus Temperature for PSBF and Solid Polystyrene Resin

Figure 13. Tensile Strain at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin

Figure 14. Compressive Strain at Proportional Limit and Ultimate Yield Versus Temperature for PSBF and Solid Polystyrene Resin

Figure 15. Dynamic Shear Modulus of 50 kg/m³ PSBF
at Various Temperatures and Testing Frequencies

Section 5

MECHANICAL PROPERTIES AS A
FUNCTION OF DENSITY

Figure 16. Tensile Yield Stress Versus Density

Figure 17. Compressive Yield Stress Versus Density

Figure 18. Tensile Modulus Versus Density

Figure 19. Compressive Modulus Versus Density

Figure 20. Dynamic Shear Modulus of PSBF as a Function of Density

Section 6

**MECHANICAL PROPERTIES AS A FUNCTION
OF n-PENTANE CONTENT**

Figure 21. Theoretical Glass Transition Temperature of PSBF and Solid Polystyrene Resin Versus n-Pentane Content

Figure 22. Ultimate Tensile Strength of PSBF Versus n-Pentane Content

Section 7

TYPICAL STRESS-STRAIN CURVES

Figure 23. Typical Stress-Strain Curves for 50 kg/m³ PSBF at Various Temperatures

Figure 24. Typical Stress-Strain Curves for 100 kg/m³ PSBF at Various Temperatures

Figure 25. Typical Stress-Strain Curves for Solid 1040 kg/m³ Polystyrene Resin at Various Temperatures

Section 8

MISCELLANEOUS GRAPHS

Figure 26. Equilibrium Moisture Content of PSBF

Figure 27. Percent of Total n-Pentane Content in Vapor Phase of PSBF

Figure 28. Vapor Pressure of n-Pentane in PSBF

Figure 29. Activity of n-Pentane in PSBF

Section 9
BIBLIOGRAPHY

BIBLIOGRAPHY

- Fossey, D. J. and Smith, C. H. "Determination of the Diffusivity of n-Pentane in Polystyrene Bead Foam," *Journal of Applied Polymer Science*, Volume 17, 1973, pp 1749-1770.
- Hammon, G. H. and Buckner, A. T. *Moisture Vapor Transmission of Polystyrene Bead Foams*, Livermore. Lawrence Livermore Laboratory, Report UCID-15587 Rev. 1, June, 1970.
- Hart, G. M., Balozs, C. F., and Clipper, R. B. "Prediction of the Long Term-Compressive Creep Behavior of Cellular Polystyrene," *Journal of Cellular Plastics*, May/June, 1973.
- Lee, W. M., "Water Vapor Permeation In Closed Cell Foams," *Journal of Cellular Plastics*, May/June, 1973.
- Rinde, J. A. *Poisson's Ratio of Rigid Plastic Foams*, Livermore: Lawrence Livermore Laboratory, Report UCID 15421, February, 1969.
- Rinde, J. A. and Hoge, K. G. *Dynamic Shear Modulus of Polystyrene Bead Foam*, Livermore: Lawrence Livermore Laboratory, Report UCRL-73457, October, 1971.
- Rinde, J. A., and Hoge, K. G. *Time and Temperature Dependence of the Mechanical Properties of Polystyrene Bead Foam*, Livermore: Lawrence Livermore Laboratory, Report UCRL-72576, July, 1970.
- Reed, R. P., Arvidson, J. M. and Durcholz, R. L. *Tensile and Compressive Testing of Polyurethane and Polystyrene Foams From 76 to 300K*, National Bureau of Standards, Boulder, Colorado, Sandia Order No., 92-4845, August 1971.
- Reed, R. P. and Arvidson, J. M. *Tensile Test Procedure and Specimens Used on Tensile Tests of Polyurethane and Polystyrene Foams at 76K*, National Bureau of Standards, Boulder, Colorado, Sandia Order No., 92-4848, April 1971.
- Skochdopole, R. E. *Development Program to Improve the Beads and Molding Process by Which Expanded Polystyrene Foams are Produced*. Final Report, Contract Number D-707596, Dow Chemical Company, July, 1971.