Benchmark Specification of Advanced Burner Test Reactor

Nuclear Science and Engineering Division

About Argonne National Laboratory

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago, at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne and its pioneering science and technology programs, see www.anl.gov.

DOCUMENT AVAILABILITY

Online Access: U.S. Department of Energy (DOE) reports produced after 1991 and a growing number of pre-1991 documents are available free at OSTI.GOV (<http://www.osti.gov/>), a service of the US Dept. of Energy's Office of Scientific and Technical Information.

Reports not in digital format may be purchased by the public from the National Technical Information Service (NTIS):

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Rd
Alexandria, VA 22312
www.ntis.gov
Phone: (800) 553-NTIS (6847) or (703) 605-6000
Fax: (703) 605-6900
Email: **orders@ntis.gov**

Reports not in digital format are available to DOE and DOE contractors from the Office of Scientific and Technical Information (OSTI):

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
www.osti.gov
Phone: (865) 576-8401
Fax: (865) 576-5728
Email: **reports@osti.gov**

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 UChicago Argonne, LLC, nor any of their employees or officers, 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 document authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, Argonne National Laboratory, or UChicago Argonne, LLC.

Benchmark Specification of Advanced Burner Test Reactor

prepared by

Taek K. Kim
Nuclear Science and Engineering Division, Argonne National Laboratory

December 16, 2020

1 Introduction

As an effort to assess the Argonne Reactor Computation (ARC) suite of fast reactor analysis codes, a numerical benchmark problem was developed using the reference 250 MWt Advanced Burner Test Reactor (ABTR) metallic core fueled with beginning of equilibrium cycle compositions (Chang et al., 2006). Material thermal expansion at operating condition was modeled by adjusting the hexagonal pitch, axial meshes, and the fuel and structure material densities appropriately. Irradiation swelling of metal fuel was considered, and the bond sodium was displaced into the lower part of fission gas plenum.

2 ABTR Benchmark Core

Figure 1 shows the core configuration of the 250 MWt ABTR benchmark problems. The core configuration was obtained from the reference ABTR core design (Chang et al., 2006). The inner and outer cores are composed of 24 and 30 driver assemblies, respectively. Nine test assembly locations were introduced in the reference ABTR core design. Among these test locations, three assemblies located in the fourth row were designated for material test assemblies, and six test assemblies located in the third and fourth rows were designated for fuel test assemblies. Since the compositions of the test assemblies are not determined at this point, material test assembly locations were loaded by reflector assemblies, while the fuel test assembly locations were loaded by the driver fuel assemblies.

Figure 1 Radial core layout of ABTR benchmark problem

Two independent safety-grade reactivity control systems are employed in ABTR reactor: primary and secondary control rod systems. The primary control system consists of one central assembly and six assemblies in fifth row, and the secondary control system consists of three assemblies in the third row. In the benchmark problem, all control assemblies are positioned above the active core.

The fuel composition at the equilibrium cycle was obtained from the REBUS-3 calculations using a lumped fission product (LFP) model. It should be emphasized here that the variation fuel compositions were extremely simplified in this benchmark and the lumped fission product was replaced by Molybdenum (Mo) because most code systems do not have the cross sections for the lumped fission product. The material information is provided in Appendix.

The assembly design data of fuel, reflector, shield and control assemblies are presented in Table 1, Table 2, Table 3, and Table 4, respectively. Since the thermal expansions of fuel and supporting material are important in ABTR core analysis, the benchmark problem was developed at the operating condition, including irradiation swelling of metal fuel. For this reason, the sodium bond (between fuel slug and cladding) is replaced to the upper gas plenum. However, the data at the room temperature are also provided for the comparison purpose.

The fuel pin and control rod are helically wrapped with wire to maintain the pin spacing such that the coolant can flow freely through the pin bundle. The wire-wrap was assumed be smeared in clad for the simplicity of the benchmark problem. Due to this reason, the outer radii of the fuel and control rod claddings are slightly increased in the benchmark problem.

At the operating condition, the metal fuel alloy is expanded radially and axially due to the thermal expansion and burnup swelling effect. The metal fuel alloy expands till contacting the inner surface of the fuel clad and glows axially along to the gas plenum, and the sodium bond is displaced to the gas plenum above the fuel. The smear density and axial swelling were assumed to be 75% and 5%, respectively.

Figure 2, Figure 3, and Figure 4 show the schematics of fuel, control and reflector/shield assemblies, respectively. Dimensions are obtained at the operating condition. All assemblies have the same lower and upper structures. A homogeneous mixture of sodium (70%) and SS-316 (30%) was assumed as the lower structure. Since the upper structure is so complicate, the upper structure is assumed to be a homogeneous mixture of the lower reflector of the fuel assembly. **Table 5** provides the average operating temperatures.

The fuel assembly contains 217 fuel pins arranged in a triangular pitch array. The fuel volume fraction at the operating condition is 31.42%. The reflector assembly contains 91 solid HT-9 pins arranged in a triangular pitch array. The HT-9 pin volume fraction is 75.2 % and the duct volume fraction is 7.7 %, yielding the total HT-9 volume fraction of 83.9 % at the operating condition. The shield assembly is mainly composed of HT-9 clad and B₄C absorber. It consists of 19 thick HT-9 tubes containing boron carbide pellets. The natural boron is used with 81% of a smeared B₄C pellet density.

The control assemblies consist of an absorber bundle contained within a duct. The absorber bundle is a closely packed array of tubes containing compacted boron carbide pellets. The bundle of pins is contained in an interior duct that channels flow through the bundle and protects the pins from damage as they slide within the outer fixed duct. The outer duct of the control rod assembly has the same external dimensions as the fuel assembly duct.

Table 1 Parameters of Fuel Assembly

	Cold	Hot
Overall length of duct, cm	340.000	341.663
Number of pins	217	
Fuel pin smear density, %	75	
Fuel pin pitch, cm	0.9080	0.9134
Fuel pin diameter, cm	0.8000	0.8048
Thickness of clad, cm	0.0520	0.0523
Outer radius of clad, cm	0.4000	0.4024
Inner radius of clad, cm	0.3480	0.3501
Fuel slug radius, cm	0.3014	0.3501
Active core height, cm	80.0000	84.4108
Gas plenum height, cm	120.0000	120.5868
Assembly pitch, cm	14.5980	14.6850
Duct outer Flat-to-Flat distance, cm	14.1980	14.2826
Duct wall thickness, cm	0.3000	0.3018
Duct inside flat-to-flat distance, cm	13.5980	13.6790
Wire wrap radius, cm	0.0515	
Wire wrap axial pitch, cm	20.3200	
Clad outer radius with wire-wrap, cm		0.4057
Lower reflector height, cm	60.000	60.293
length of displaced sodium bond, cm	0.0000	19.7637
Volume fraction		
- Fuel	0.3355	0.3142
- Clad	0.1536	0.1510
- Duct	0.0783	0.0770
- Sodium bond	0.1118	0.0000
- Coolant	0.3208	0.3208

Table 2 Parameters of Reflector Assembly

	Cold	Hot
Overall length of duct, cm	340.000	341.663
Number of pins	91	
Pin pitch, cm	1.4067	1.4151
Reflector rod diameter, cm	1.4052	1.4136
Reflector rod radius, cm	0.7026	0.7068
Reflector rod height, cm	260.0000	261.2714
Assembly pitch, cm	14.5980	14.6850
Duct outer flat-to-flat distance, cm	14.1980	14.2826
Duct wall thickness, cm	0.3000	0.3018
Duct inside flat-to-flat distance, cm	13.5980	13.6790
Volume fraction		
- Fuel	0.76470	0.75199
- Duct	0.07826	0.07696
- Coolant	0.15704	0.15704

Table 3 Parameters of Shield Assembly

	Cold	Hot
Overall length of duct, cm	340.000	341.663
Number of pins	19	
Shield pin pitch, cm	3.0441	3.0622
Absorber smear density, %	81	
Shield pin diameter, cm	3.0426	3.0607
Thickness of clad, cm	0.2500	0.2515
Outer radius of clad, cm	1.5213	1.5304
Inner radius of clad, cm	1.2713	1.2789
Absorber radius, cm	1.1442	1.2789
Absorber height, cm	260.0000	261.2714
Assembly pitch, cm	14.5980	14.6850
Duct outer flat-to-flat distance, cm	14.1980	14.2826
Duct wall thickness, cm	0.3000	0.3018
Duct inside flat-to-flat distance, cm	13.5980	13.6790
Volume fraction		
- Fuel	0.42341	0.41637
- Clad	0.22580	0.22050
- Duct	0.07826	0.07696
- He bond	0.09932	0.00000
- Coolant	0.17320	0.17320

Table 4 Parameters of Control Assembly

	Cold	Hot
Overall length of duct, cm	340.000	341.663
Number of pins	91	
Rod pitch	1.2484	1.2558
Absorber smear density, %	85	
pin diameter, cm	1.1104	1.1170
Thickness of clad, cm	0.0700	0.0704
Outer radius of clad, cm	0.5552	0.5585
Inner radius of clad, cm	0.4852	0.4881
Absorber radius, cm	0.4473	0.4881
Absorber height, cm	85.0000	85.4157
Assembly pitch, cm	14.5980	14.6850
Duct outer flat-to-flat distance, cm	14.1980	14.2826
Duct wall thickness, cm	0.3000	0.3018
Duct inside flat-to-flat distance, cm	13.5980	13.6790
Inner duct outer flat-to-flat distance, cm	12.7980	12.8743
Inner duct inner flat-to-flat distance, cm	12.1980	12.2707
Wire wrap radius, cm	0.0665	
Wire wrap axial pitch, cm	20.3200	
Clad outer radius with wire-wrap		0.5626
Radius of follower	5.0000	5.0298
Length of follower	16.8000	16.8822
Volume fraction		
- Fuel	0.30996	0.30481
- Clad	0.11979	0.11780
- Duct	0.14864	0.14617
- He bond	0.05470	0.00000
- Coolant	0.36691	0.36692

Table 5 Temperature at Operating Condition

	Temperature (°C)
Active core	
Coolant	432.5
Structure	462.5
Fuel	582.5
Reflector	432.5
Shield	355.0
Lower structure and reflector	355.0
Upper plenum and structure	510.0

Figure 2 Fuel Assembly Schematics

Figure 3 Control Assembly Schematics

Figure 4 Radial Reflector/Shield Assembly Schematics

Reference

Chang, Y. I., et al. (2006), "Advanced Burner Test Reactor Preconceptual Design Report," ANL-ABR-1, ANL-AFCI-173, Argonne National Laboratory, September 5, 2006.

Appendix Composition Number Densities (/barn-cm)

1. Lower Structure

Na	1.5591E-02
Fe	1.5878E-02
Ni	3.2604E-03
Cr	3.2355E-03
Mn55	5.0846E-04
Mo	4.3524E-04

2. Lower Reflector of fuel assembly

	Heterogeneous			Homogeneous
	Clad & str.	Coolant	Duct	
Na		2.2272E-02		7.1455E-03
Fe	6.9844E-02		6.9844E-02	4.7436E-02
Ni	4.3063E-04		4.3063E-04	2.9248E-04
Cr	1.0385E-02		1.0385E-02	7.0532E-03
Mn55	4.6007E-04		4.6007E-04	3.1247E-04
Mo	4.9097E-04		4.9097E-04	3.3346E-04

3. Active Fuel

Nuclide	Heterogeneous			Clad	Coolant Sodium	Duct HT9
	inner core	middle core	outer core	HT9		
U-234	1.2225E-08	1.0027E-06	1.4997E-08			
U-235	3.2248E-05	3.2038E-05	3.1767E-05			
U-236	2.0561E-06	1.9484E-06	1.8593E-06			
U-238	2.0222E-02	1.9745E-02	1.9317E-02			
Np237	3.8387E-06	1.8093E-04	3.1274E-06			
Pu236	1.3918E-11	9.0759E-10	9.1074E-12			
Pu238	9.5854E-07	9.0509E-05	9.8743E-07			
Pu239	3.4991E-03	2.3546E-03	4.3068E-03			
Pu240	3.7398E-04	1.0881E-03	4.5617E-04			
Pu241	2.4535E-05	2.9432E-04	2.9545E-05			
Pu242	1.7542E-06	2.1919E-04	2.0615E-06			
Am241	1.4209E-06	2.1306E-04	2.2274E-06			
Am242m	2.8475E-08	5.8336E-06	4.0761E-08			
Am243	6.1338E-08	4.3624E-05	7.5588E-08			
Cm242	4.7083E-08	7.3545E-06	5.6294E-08			
Cm243	7.4138E-10	2.4428E-07	9.0540E-10			
Cm244	4.8305E-09	1.0986E-05	5.5302E-09			
Cm245	1.9064E-10	9.7716E-07	1.9972E-10			

Cm246	2.6112E-12	6.7680E-08	2.4070E-12			
Zr	7.2938E-03	7.2938E-03	7.2938E-03			
Na					2.2272E-02	
Fe				6.9844E-02		6.9844E-02
Ni				4.3063E-04		4.3063E-04
Cr				1.0385E-02		1.0385E-02
Mn55				4.6007E-04		4.6007E-04
Mo	9.76123E-04	8.36399E-04	9.81845E-04	4.9097E-04		4.9097E-04

Nuclide	Homogeneous		
	Inner core	middle core	outer core
U-234	5.46898E-09	4.48578E-07	6.70877E-09
U-235	1.44262E-05	1.43324E-05	1.42111E-05
U-236	9.19798E-07	8.71638E-07	8.31760E-07
U-238	9.04638E-03	8.83280E-03	8.64147E-03
Np237	1.71727E-06	8.09410E-05	1.39907E-06
Pu236	6.22636E-12	4.06014E-10	4.07421E-12
Pu238	4.28807E-07	4.04893E-05	4.41730E-07
Pu239	1.56532E-03	1.05336E-03	1.92666E-03
Pu240	1.67301E-04	4.86743E-04	2.04069E-04
Pu241	1.09760E-05	1.31667E-04	1.32172E-05
Pu242	7.84751E-07	9.80540E-05	9.22204E-07
Am241	6.35636E-07	9.53142E-05	9.96453E-07
Am242m	1.27384E-08	2.60969E-06	1.82346E-08
Am243	2.74399E-08	1.95154E-05	3.38145E-08
Cm242	2.10628E-08	3.29008E-06	2.51831E-08
Cm243	3.31661E-10	1.09281E-07	4.05034E-10
Cm244	2.16096E-09	4.91452E-06	2.47394E-09
Cm245	8.52838E-11	4.37138E-07	8.93442E-11
Cm246	1.16811E-12	3.02767E-08	1.07680E-12
Zr	3.26289E-03	3.26289E-03	3.26289E-03
Na	7.14528E-03	7.14528E-03	7.14528E-03
Fe	1.61921E-02	1.61921E-02	1.61921E-02
Ni	9.98349E-05	9.98349E-05	9.98349E-05
Cr	2.40756E-03	2.40756E-03	2.40756E-03
Mn55	1.06659E-04	1.06659E-04	1.06659E-04
Mo	5.50492E-04	4.87986E-04	5.53051E-04

- Na density of homogeneous voided case is 1.2039E-3

4. Gas plenum of fuel assembly with displaced sodium bond

	Heterogeneous			Homogeneous
	Clad	Coolant	Duct	
Na		2.2272E-02		1.7109E-02
Fe	6.9844E-02		6.9844E-02	1.6192E-02
Ni	4.3063E-04		4.3063E-04	9.9831E-05
Cr	1.0385E-02		1.0385E-02	2.4075E-03
Mn55	4.6007E-04		4.6007E-04	1.0666E-04
Mo	4.9097E-04		4.9097E-04	1.1382E-04

- Na density of homogeneous voided case is 1.1167E-2

5. Gas plenum of fuel assembly without displaced sodium bond

	Heterogeneous			Homogeneous
	Clad	Coolant	Duct	
Na		2.2272E-02		7.1455E-03
Fe	6.9844E-02		6.9844E-02	1.6192E-02
Ni	4.3063E-04		4.3063E-04	9.9831E-05
Cr	1.0385E-02		1.0385E-02	2.4075E-03
Mn55	4.6007E-04		4.6007E-04	1.0666E-04
Mo	4.9097E-04		4.9097E-04	1.1382E-04

- Na density of homogeneous voided case is 1.2039E-3

6. Empty under Control Rod

	Heterogeneous		Homogeneous
Nuclide	Coolant	Duct	
Na	2.2272E-02		2.0529E-02
Fe		6.9844E-02	5.4661E-03
Ni		4.3063E-04	3.3702E-05
Cr		1.0385E-02	8.1273E-04
Mn55		4.6007E-04	3.6006E-05
Mo		4.9097E-04	3.8424E-05

7. Control rod follower

	Heterogeneous			Homogeneous
Nuclide	Follower	Coolant	Duct	
Na		2.22724E-02		1.1051E-02
Fe	5.2048E-02		6.9844E-02	2.7616E-02
Ni	1.0687E-02		4.3063E-04	4.5819E-03
Cr	1.0606E-02		1.0385E-02	5.3263E-03
Mn55	1.6667E-03		4.6007E-04	7.4530E-04
Mo	1.4267E-03		4.9097E-04	6.4558E-04

8. Control rod

	Heterogeneous				Homogeneous
Nuclide	Absorber	Clad	Coolant	Duct	
C	4.0679E-03				1.4834E-03
B10	1.6441E-02				5.9956E-03
B11	6.6179E-02				2.4133E-02
Na			2.2272E-02		8.1722E-03
Fe		6.9844E-02		6.9844E-02	1.8747E-02
Ni		4.3063E-04		4.3063E-04	1.1559E-04
Cr		1.0385E-02		1.0385E-02	2.7875E-03
Mn55		4.6007E-04		4.6007E-04	1.2349E-04
Mo		4.9097E-04		4.9097E-04	1.3179E-04

9. Gas plenum of control rod

	Heterogeneous			Homogeneous
Nuclide	Clad	Coolant	Duct	
Na		2.2272E-02		8.1722E-03
Fe	6.9844E-02		6.9844E-02	1.8747E-02
Ni	4.3063E-04		4.3063E-04	1.1559E-04
Cr	1.0385E-02		1.0385E-02	2.7875E-03
Mn55	4.6007E-04		4.6007E-04	1.2349E-04
Mo	4.9097E-04		4.9097E-04	1.3179E-04

10. Reflector

	Heterogeneous			Homogeneous
Nuclide	solid rod	Coolant	Duct	
Na		2.2272E-02		3.4976E-03
Fe	6.9844E-02		6.9844E-02	5.8876E-02
Ni	4.3063E-04		4.3063E-04	3.6301E-04
Cr	1.0385E-02		1.0385E-02	8.7541E-03
Mn55	4.6007E-04		4.6007E-04	3.8782E-04
Mo	4.9097E-04		4.9097E-04	4.1387E-04

11. Shield

	Heterogeneous				Homogeneous
Nuclide	Absorber	Clad	Coolant	Duct	
C	3.7154E-03				1.9422E-03
B10	1.5668E-02				8.1900E-03
B11	6.3065E-02				3.2966E-02
Na			2.2272E-02		3.8576E-03
Fe		6.9844E-02		6.9844E-02	2.1237E-02
Ni		4.3063E-04		4.3063E-04	1.3094E-04
Cr		1.0385E-02		1.0385E-02	3.1577E-03
Mn55		4.6007E-04		4.6007E-04	1.3989E-04
Mo		4.9097E-04		4.9097E-04	1.4929E-04

12. Outside core

	Heterogeneous		Homogeneous
	Barrel	Coolant	
Na		2.22724E-02	1.81469E-02
Fe	5.20478E-02		9.64075E-03
Ni	1.06872E-02		1.97959E-03
Cr	1.06058E-02		1.96450E-03
Mn55	1.66670E-03		3.08720E-04
Mo	1.42668E-03		2.64263E-04

Nuclear S Engineering Division

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439

www.anl.gov