Contents

Abo Pre	out the face of	-		xi xv xxix xxxiii		
1.	Over	view of	high temperature gas-cooled reactor	1		
	Jin Iwatsuki, Kazuhiko Kunitomi, Hideaki Mineo, Tetsuo Nishihara,					
			ıba, Masayuki Shinozaki, Yukio Tachibana and Xing Yan			
	1.1		es of high temperature gas-cooled reactor	1		
			Structure and materials	1		
			Heat application	3		
			Safety	4		
			Adaptability to environment	6		
			of research and development in world	7		
		-	of research and development in Japan	11		
	Refer	rences		15		
2.	Design of High Temperature Engineering Test Reactor (HTTR) Yusuke Fujiwara, Minoru Goto, Kazuhiko Iigaki, Tatsuo Iyoku, Hai Quan Ho, Taiki Kawamoto, Makoto Kondo, Kazuhiko Kunitomi, Keisuke Morita, Satoru Nagasumi, Shigeaki Nakagawa, Tetsuo Nishihara, Naoki Nojiri, Masato Ono, Akio Saikusa, Nariaki Sakaba, Taiju Shibata, Yosuke Shimazaki, Atsushi Shimizu, Masayuki Shinozaki, Junya Sumita, Yukio Tachibana, Shoji Takada, Daisuke Tochio, Takahiro Uesaka and Shohei Ueta					
	2.1		riew of HTTR design features	18		
			Introduction	18		
			History and future plan of HTTR project	19		
			Major design features of HTTR	23		
	2.2		R&D programs for HTTR	29		
	2.2		ar design	32		
			Introduction	32		
			Design requirement	32		
			Analytical method Evaluation of nuclear characteristics	34		
	2.2			35		
	2.3		thermal-hydraulics	41		
		2.3.1	Introduction	41		

vi

	2.3.2	Design requirements	41	
		Design details	42	
	2.3.4	Evaluation results of design	44	
	2.3.5	Reevaluation of maximum fuel temperature with		
		operational data	45	
2.4	Graph	ite components	48	
	2.4.1	Introduction	48	
	2.4.2	In-core graphite and carbon structure in high temperature		
		engineering test reactor	48	
	2.4.3	Concepts of graphite design criteria	50	
		Quality control	58	
2.5		ic components	58	
		Introduction	58	
		Development of Hastelloy XR	59	
		Identification of failure modes	61	
		Developments of design limits and rules	61	
2.6		components and reactor internals	71	
		Introduction	71	
	2.6.2		71	
		Hexagonal graphite blocks	74	
		Core support structures	79	
		Core support metallic structures	85	
		Shielding blocks	87	
2.7	Seismic design			
		Introduction	89	
		Seismic design	90	
		Geological composition and seismometry	94	
		Structure of core components	94	
		Development of evaluation method	99	
	2.7.6		100	
2.8	Coolin	ng system	102	
		Introduction	102	
	2.8.2	Primary cooling system	103	
		Secondary helium cooling system	110	
		Pressurized water-cooling system	112	
		Residual heat removal system	113	
2.9	Reacti	vity control system	113	
		Introduction	113	
	2.9.2	Control rod system	114	
	2.9.3	Reserve shutdown system	126	
2.10	Instrumentation and control system			
	2.10.1	· · · · · · · · · · · · · · · · · · ·	127	
	2.10.2	Instrumentation system	128	
	2.10.3	· · · · · · · · · · · · · · · · · · ·	131	
		Control system	132	

Contents

		2.10.5	Safety protection system	134		
		2.10.6	Performance test results	135		
	2.11	Conta	inment structures	138		
			Introduction	138		
			Reactor containment vessel	138		
		2.11.3	Service area	146		
		2.11.4	Emergency air purification system	147		
	2.12		systems	151		
		2.12.1	Introduction	151		
			2. Auxiliary helium systems	151		
			Fuel system	155		
	2.13		design	158		
			Introduction	158		
			Basic safety design philosophy	158		
		2.13.3	•	160		
			Fundamental safety functions unique to HTTR	164		
		2.13.5	±	165		
			Selection of events	167		
			Safety evaluation technologies	169		
		2.13.8	New safety criteria	173		
	Refe	rences		173		
3.	R&I	&D on components 179				
•	Jun 1	un Aihara, Minoru Goto, Yoshiyuki Inagaki, Tatsuo Iyoku,				
	Kazu	Kazuhiko Kunitomi, Tetsuo Nishihara, Nariaki Sakaba, Taiju Shibata,				
	Juny	Junya Sumita, Yukio Tachibana, Shoji Takada, Tetsuaki Takeda and				
	Shoh	ei Ueta				
	3.1	Fuel		180		
		3.1.1	Introduction	180		
		3.1.2	Related research and development for fuel design	181		
		3.1.3	Fabrication technologies for HTTR fuel	185		
		3.1.4	Performance of HTTR fuel during long-term high			
			temperature operation	189		
	3.2		omponents and reactor internals	191		
			Introduction	191		
		3.2.2	Tests on core components	191		
		3.2.3	Tests on reactor internals	196		
	3.3		cooling system	203		
			Introduction	203		
			Experiment	205		
			Numerical method	208		
			Evaluation of hot spot by natural convection	213		
			Evaluation of local hot spot around standpipes	215		
	3.4		ediate heat exchanger	217		
			Introduction	217		
		3.4.2	Creep collapse of the tube against external pressure	218		

viii Contents

		3.4.3	Creep fatigue of tube against thermal stress	220
		3.4.4	Seismic behavior of tube bundle	223
		3.4.5	Thermal hydraulic behavior of tube bundle	226
		3.4.6	In-service inspection technology of tube	228
	3.5	Basic	feature of air ingress during primary pipe rupture accident	230
			Introduction	230
		3.5.2	Basic feature of air ingress phenomena in a reverse	
			U-shaped channel	233
		3.5.3	Basic feature of air ingress phenomena in a simulated	
			reactor apparatus	243
	Refe	erences		253
4.	Оре	ration	of HTTR	257
	_		, Minoru Goto, Hiroyuki Inoi, Etsuo Ishitsuka, Tatsuo Iyoku,	
		-	unitomi, Shigeaki Nakagawa, Tetsuo Nishihara, Hai Quan Ho,	
	Akic	Saikusa	a, Nariaki Sakaba, Hiroaki Sawahata, Taiju Shibata,	
	Mas	ayuki Sl	hinozaki, Yukio Tachibana, Shoji Takada,	
	Kun	iyoshi T	akamatsu and Daisuke Tochio	
	4.1	Unexp	pected incidents under construction and operation	258
		4.1.1	Introduction	258
			Temperature rise of primary upper shielding	258
		4.1.3	Temperature rise of core support plate	264
	4.2		cteristic test of initial core	269
			Introduction	269
			General description	270
			Critical approach	271
			Excess reactivity and shutdown margin	272
			Control rod characteristics	274
			Reactivity coefficient	275
	1.2	4.2.7	Neutron flux and power distribution	276
	4.3		mance test	278
		4.3.1 4.3.2	Introduction Major test items	278 279
		4.3.2	Major test items Heat balance of reactor cooling system	280
		4.3.4	Heat exchanger performance	281
		4.3.5	Reactor control system performance	282
		4.3.6	Residual heat removal performance at manual reactor scram	284
		4.3.7	Thermal expansion performance of high temperature	204
		1.3.7	components	285
		4.3.8	Fuel and fission product behavior	286
	4.4		temperature operation	287
		4.4.1	Introduction	287
		4.4.2	Main test results of long-term high temperature operation	288
		4.4.3	Validation using high temperature engineering test reactor	
			burnup data	292

Contents ix

	4.5		demonstration test Introduction	298
				298
			High temperature engineering test reactor control system	300
		4.5.3	Safety demonstration test plan	302
			Analysis code and model	303
			Reactivity insertion test	304
			Coolant flow reduction test—gas circulators trip test	307
	Refe	4.5.7 rences	Loss of forced cooling test	309 310
5.	D & T) on cor	nmercial high temperature gas-cooled reactor	313
٥.			Takeshi Aoki, Yuji Fukaya, Minoru Goto, Yoshiyuki Imai,	313
			naba, Yoshiyuki Inagaki, Tatsuo Iyoku, Yu Kamiji,	
			ra, Shinji Kubo, Kazuhiko Kunitomi, Naoki Mizuta,	
			yagmarjav, Tetsuo Nishihara, Hiroki Noguchi,	
			ashi, Nariaki Sakaba, Koei Sasaki, Hiroyuki Sato,	
			a, Junya Sumita, Yukio Tachibana, Shoji Takada,	
			eda, Hiroaki Takegami, Nobuyuki Tanaka,	
			and Xing Yan	
	5.1		n design for power generation	314
	3.1		Introduction	314
			HTR50S: HTGR steam cycle power plant	315
			GTHTR300: HTGR gas turbine power plant	319
	5.2		n design for cogeneration	329
	3.2		Introduction	329
			Hydrogen cogeneration	330
			Seawater desalination	336
			HTGR renewable hybrid system	338
	5.3		n design for steelmaking	341
	0.0	-	Introduction	341
			Flow diagram of steelmaking systems	341
			CO ₂ emission	346
		5.3.4	Steelmaking cost	346
	5.4		design for connection of heat application system	
			igh temperature gas-cooled reactor	349
			Introduction	349
		5.4.2	Roadmap for safety standard establishment	349
		5.4.3	Safety requirements	351
		5.4.4	Basic concept of safety guides	353
		5.4.5	HTTR cogeneration demonstration	355
	5.5		urbine technology for power generation	359
		5.5.1	Introduction	359
		5.5.2	Helium gas compressor	360
			Magnetic bearing	366

Contents

5.6	Iodine	-sulfur process technology for hydrogen production	370
	5.6.1	Introduction	370
	5.6.2	Bench-scale test	371
	5.6.3	Elemental technologies	371
	5.6.4	Industrial material component test	372
	5.6.5	Hydrogen production test	377
	5.6.6	Improvement of hydrogen production efficiency	379
	5.6.7	Component materials	383
5.7	Systen	n integration technology for connection of heat	
	applica	ation system and high temperature gas-cooled reactor	387
	5.7.1	Introduction	387
	5.7.2	Control technology	389
	5.7.3	Tritium permeation	393
	5.7.4	Explosion of combustible gas	396
	5.7.5	High temperature isolation valves	397
5.8	Preven	ation technology for air ingress during a primary	
	pipe ru	upture accident	399
	5.8.1	Introduction	399
	5.8.2	Prevention technology of air ingress in a reverse	
		U-shaped channel	399
	5.8.3	Basic feature of air ingress phenomena during a	
		horizontal pipe break accident	415
5.9	Advan	ced fuel technology for high burnup	421
	5.9.1	Introduction	421
	5.9.2	Design of high burnup fuel	422
	5.9.3	Upgrade technologies for high burnup	424
	5.9.4	Future study plan	429
5.10	Advan	ced fuel for plutonium burner	429
	5.10.1	Introduction	429
	5.10.2	Fuel fabrication process of Clean Burn	430
	5.10.3	Core design	432
	5.10.4	Future study plan	436
5.11	Advan	ced fuel technology for reduction of high-level	
	radioa	ctive waste	437
	5.11.1	Introduction	437
	5.11.2	Calculation for repository design	437
	5.11.3		441
Refer	ences		445
Index			451