

## CONTENTS

<b>I. INTRODUCTION .....</b>	<b>1</b>
References to Chapter I .....	3
<b>II. SUMMARY .....</b>	<b>5</b>
1. Impurity control – critical issue .....	5
1.1. General .....	5
1.2. Impurity control issues .....	6
1.2.1. Physics considerations .....	6
1.2.2. Engineering considerations .....	7
1.3. Poloidal divertor .....	8
1.3.1. Physics issues .....	8
1.3.2. Engineering trade-off studies .....	8
1.4. Pumped limiter .....	11
1.5. Reference impurity control system .....	12
2. RF heating and current drive .....	12
2.1. Heating to ignition .....	12
2.2. Non-inductive current drive .....	13
2.3. Startup assist and profile control .....	15
2.4. Launcher design concepts .....	15
3. Transient electromagnetics .....	16
3.1. Plasma stabilization .....	17
3.2. Startup .....	18
3.3. Disruption .....	18
4. Maintainability .....	18
4.1. Assessment and analysis for the different maintenance concepts .....	19
4.1.1. Design requirements and assumption for both maintenance concepts .....	19
4.1.2. Tritium containment and cleanup .....	19
4.1.3. Bakeout and pumpdown criteria .....	19
4.1.4. Atmospheric tritium recovery .....	20
4.1.5. Shielding requirements and machine configuration..	21
4.1.6. Maintenance scenarios .....	21
4.1.7. Maintenance equipment .....	21
4.2. Comparison of both design approaches .....	21

5.	Technical benefit of partitioning INTOR component design and fabrication .....	22	1.2.1.	Experimental data base for poloidal divertors .....	60
6.	Physics data base .....	24	1.2.1.1.	Credibility of high-recycling regime .....	60
6.1.	Stability limits .....	24	1.2.1.2.	Credibility of high recycling in an open geometry .....	64
6.2.	Non-DT contributions to beta .....	25	1.2.1.3.	Plasma edge conditions in the 'H-mode'..	65
6.3.	Confinement .....	25	1.2.1.4.	Impurity control .....	66
6.3.1.	Energy confinement .....	25	1.2.1.5.	Power balance .....	68
6.3.2.	Particle confinement .....	27	1.2.1.6.	Gas pumping from the divertor .....	69
6.3.3.	Momentum confinement .....	27	1.2.1.7.	Scrape-off and divertor plasma transport .....	70
6.4.	Neutral-beam heating and current drive .....	29	1.2.2.	Divertor modelling .....	70
6.5.	Operation scenario .....	29	1.2.2.1.	Two-dimensional models .....	71
6.6.	Burning plasma .....	30	1.2.2.2.	Modelling of ASDEX .....	73
6.7.	Plasma diagnostics .....	30	1.2.2.3.	Modelling of PDX .....	74
7.	Engineering data base .....	31	1.2.2.4.	Modelling of Doublet-III .....	75
7.1.	Systems engineering .....	31	1.2.2.5.	Conclusions of interpretative modelling..	77
7.2.	Magnets .....	31	1.2.3.	Predictive modelling of the single-null poloidal divertor for the high-recycling regime in INTOR ....	78
7.3.	Vacuum enclosure and vacuum technology .....	33	1.2.3.1.	Modelling of the high-recycling regime ....	78
7.4.	Neutral-beam heating systems .....	33	1.2.3.2.	Impurity transport in INTOR .....	86
7.5.	Pellet injection .....	34	1.2.3.3.	Pumping of helium .....	88
7.6.	Radiation-hardened diagnostics and instrumentation .....	34	1.2.3.4.	Optimization of geometry .....	88
8.	Nuclear data base assessment .....	34	1.2.3.5.	Conclusions from modelling .....	88
8.1.	Blanket .....	34	1.2.4.	Impact upon the design concept .....	89
8.2.	Shield .....	38	1.2.4.1.	Height of divertor chamber .....	89
8.3.	Tritium .....	39	1.2.4.2.	Comparison of single- and double-null divertors .....	90
8.4.	Safety .....	39	1.3.	Limiter .....	91
9.	INTOR role and objectives .....	41	1.3.1.	Experimental data base for limiters .....	91
9.1.	Role of INTOR in the fusion programme .....	41	1.3.1.1.	Impurity control .....	92
9.2.	INTOR objectives .....	43	1.3.1.2.	Pumping performance .....	93
10.	Design concept .....	45	1.3.1.3.	Effect upon plasma confinement .....	94
11.	Operation and test programme .....	51	1.3.1.4.	Scrape-off plasma conditions .....	96
11.1.	Operational requirements .....	51	1.3.2.	Limiter modelling .....	97
11.1.1.	Fluence requirements for structural materials radiation damage tests .....	52	1.3.3.	Two-dimensional predictive modelling .....	98
11.1.2.	Blanket testing requirements .....	52	1.3.4.	Impact upon the INTOR design concept .....	99
11.1.3.	Long-term operation component reliability .....	54	1.4.	Innovative schemes .....	99
11.2.	Operation schedule and test programme .....	54	1.4.1.	Data on electric field effects .....	99
<b>III. IMPURITY CONTROL</b>	.....	55	1.4.2.	Data on ergodic limiters .....	100
0.	Introduction .....	55	1.4.3.	Experimental data and modelling of the bundle divertor .....	101
1.	Impurity control physics .....	55	1.4.3.1.	Performance of divertor .....	102
1.1.	Introduction to physics .....	55	1.4.3.2.	Models and their validation .....	104
1.2.	Poloidal divertor .....	58	1.4.3.3.	Extrapolation to INTOR .....	105

1.4.4.	Data on RF pumpout .....	105	2.4.2.3.	Sputtering coefficients .....	136
1.4.5.	Data on flow reversal .....	106	2.4.2.4.	Hydrogen permeation and embrittlement .....	136
1.4.6.	Liquid and droplet limiters .....	107	2.5.	Fabrication .....	137
1.5.	Fuelling .....	108	2.5.1.	Structural materials .....	137
1.5.1.	Data on gas fuelling .....	109	2.5.2.	Plasma side materials .....	138
1.5.2.	Data on pellet injection .....	110	2.5.3.	Bimetallic bonds .....	138
1.6.	Basic science data .....	110	2.6.	Thermal hydraulic and stress analysis .....	141
1.6.1.	Atomic processes .....	111	2.6.1.	Divertor temperature distribution .....	141
1.6.1.1.	Electron collisions with hydrogen atoms .....	111	2.6.2.	Divertor stress distribution .....	141
1.6.1.2.	Proton collisions with hydrogen atoms ...	112	2.6.3.	Alternative coolants .....	144
1.6.1.3.	Electron collisions with impurity species .....	113	2.7.	Electromagnetics .....	146
1.6.1.4.	Collisions between hydrogen atoms and impurity ions .....	114	2.8.	Disruptions .....	147
1.6.1.5.	Collisions between protons and impurity ions .....	115	2.8.1.	Thermal response .....	147
1.6.1.6.	Interactions with hydrogen molecules ....	115	2.8.2.	Liquid-metal kinetics .....	148
1.6.1.7.	Sources of data .....	116	2.8.2.1.	Hydrodynamic instability of the melt layer .....	149
1.6.2.	Surface interaction .....	116	2.8.2.2.	Melt layer movement .....	150
1.6.3.	Basic data for plasma transport .....	119	2.8.2.3.	Helium bubble formation .....	150
1.7.	Data on vacuum vessel preparation .....	120	2.8.3.	Experimental and metallurgical observations .....	151
1.8.	Physics conclusions and R and D .....	121	2.9.	Sputtering erosion/redeposition .....	153
2.	Engineering .....	125	2.9.1.	Erosion and deposition profiles .....	153
2.1.	Introduction .....	125	2.9.2.	Models and calculations .....	153
2.2.	Operating conditions .....	125	2.9.3.	Properties of redeposited materials .....	154
2.2.1.	Common parameters .....	125	2.10.	Lifetime analysis .....	155
2.2.2.	High-recycling divertor and first wall .....	129	2.10.1.	Divertor .....	156
2.3.	Mechanical configuration .....	129	2.10.2.	First wall .....	158
2.3.1.	Limiter .....	129	2.10.3.	Long-pulse operation .....	161
2.3.2.	Divertor .....	131	2.11.	Tritium permeation .....	162
2.3.2.1.	Plate .....	131	2.11.1.	Through divertor .....	163
2.3.2.2.	Chamber .....	134	2.11.2.	Through first wall .....	163
2.4.	Materials considerations .....	134	2.12.	Vacuum pumping .....	164
2.4.1.	Structural materials .....	134	2.12.1.	Requirements .....	164
2.4.1.1.	Physical and mechanical properties .....	134	2.12.2.	Vacuum pumps and pumping efficiency .....	164
2.4.1.2.	Irradiation properties .....	134	2.12.3.	Thermalization of divertor exhaust .....	165
2.4.1.3.	Coolant compatibility .....	135	2.13.	Alternative concepts .....	166
2.4.1.4.	Hydrogen permeation and embrittlement .....	135	2.13.1.	Evaluation of a copper-lithium alloy for use in the INTOR impurity control system .....	166
2.4.2.	Plasma side materials .....	136	2.13.2.	Self-pumping of helium by in-situ metal deposition .....	167
2.4.2.1.	Physical and mechanical data .....	136	2.13.3.	Divertor concepts with collector plates covered by liquid-metal film .....	167
2.4.2.2.	Irradiation effects .....	136			

2.14.	Data base .....	169	2.2.	Data base and application to INTOR .....	214
2.14.1.	Impurity control and first-wall design requirements .....	169	2.2.1.	Plasma heating and current drive .....	214
2.14.2.	Reviews .....	169	2.2.1.1.	Experimental status .....	214
	2.14.2.1. Review of Phase Zero, One and Two A assessments .....	169	2.2.1.2.	Theory and modelling .....	222
	2.14.2.2. Review of data base .....	172	2.2.1.3.	Comparison between models and experiment .....	226
2.14.3.	R and D requirements .....	186	2.2.1.4.	Modelling applications to INTOR .....	229
	2.14.3.1. Present R and D to five years ahead ....	186	2.2.2.	Non-inductive startup and startup assist .....	231
	2.14.3.2. Test facilities .....	187	2.2.3.	Launcher design and technology .....	232
	2.14.3.3. Needed R and D programmes .....	188	2.2.4.	Characteristics and concepts of INTOR launchers...	235
3.	Conclusions .....	189	2.3.	R and D programmes .....	236
	References to Chapter III .....	190	2.3.1.	Ongoing programmes and expected advances .....	236
			2.3.1.1.	Physics .....	236
			2.3.1.2.	Technology .....	237
			2.3.2.	Additional R and D needs .....	239
			2.3.2.1.	Physics .....	239
			2.3.2.2.	Technology .....	239
			2.4.	Conclusions for INTOR .....	239
IV.	RF HEATING AND CURRENT DRIVE .....	191	3.	Electron cyclotron waves .....	241
1.	Ion cyclotron waves .....	191	3.1.	INTOR design assumptions and parameters (Phase Two A Part 1) .....	241
1.1.	INTOR design assumptions and parameters (Phase Two A Part 1) .....	191	3.2.	Data base and application to INTOR .....	242
1.2.	Data base and application to INTOR .....	191	3.2.1.	Plasma heating .....	242
1.2.1.	Plasma heating .....	191	3.2.1.1.	Experimental status .....	242
	1.2.1.1. Experimental status .....	191	3.2.1.2.	Theory and modelling .....	243
	1.2.1.2. Theory and modelling .....	198	3.2.1.3.	Comparison between models and experiments .....	244
	1.2.1.3. Comparison between models and experiments .....	199	3.2.2.	Startup assist .....	244
	1.2.1.4. Modelling applications to INTOR .....	201	3.2.3.	Current drive .....	246
1.2.2.	Startup assist .....	204	3.2.4.	Launcher design and technology .....	246
1.2.3.	Current drive .....	204	3.2.5.	Characteristics and concepts of INTOR launchers...	247
1.2.4.	Launcher design and technology .....	205	3.3.	R and D programmes .....	249
1.2.5.	Characteristics and concepts of INTOR launchers...	209	3.3.1.	Ongoing programmes and expected advances .....	249
1.3.	R and D programmes .....	211	3.3.1.1.	Physics .....	249
1.3.1.	Ongoing programmes and expected advances .....	211	3.3.1.2.	Technology .....	250
	1.3.1.1. Physics .....	211	3.3.2.	Additional R and D needs .....	250
	1.3.1.2. Technology .....	211	3.3.2.1.	Physics .....	250
1.3.2.	Additional R and D needs .....	212	3.3.2.2.	Technology .....	250
	1.3.2.1. Physics .....	213	3.4.	Conclusions for INTOR .....	251
	1.3.2.2. Technology .....	213	4.	Other methods for heating and/or current drive .....	251
1.4.	Conclusions for INTOR .....	213	4.1.	Introductory remarks .....	251
2.	Lower hybrid waves .....	214	4.2.	Data base assessment .....	251
2.1.	INTOR design assumptions and parameters (Phase Two A Part 1) .....	214	4.2.1.	Alfvén waves .....	251
			4.2.2.	Adiabatic compression .....	254

4.2.3.	Magnetic pumping .....	255	6.2.4.	Analytical tools – R and D programmes .....	315
4.2.4.	Turbulent heating .....	255	6.2.5.	Coupled electromagnetic/mechanical/transient code development .....	315
4.2.5.	Electron beams .....	256	6.2.6.	Axisymmetric plasma evolution code development .....	315
4.2.6.	Cyclotron radiation .....	257	6.2.7.	2D/3D electromagnetic code upgrades and development .....	315
	References to Chapter IV .....	257	6.2.8.	Code for multiple coil safety and protection analysis .....	316
	<b>V. TRANSIENT ELECTROMAGNETICS .....</b>	<b>259</b>	6.2.9.	Analytical tools – impact on INTOR .....	316
1.	Introduction .....	259	6.3.	Experimental data – data base assessment .....	316
2.	Plasma stabilization .....	260	6.3.1.	Arcing voltage .....	316
2.1.	Summary of plasma stabilization experimental experience ....	261	6.3.2.	Experimental data for code validation .....	316
2.2.	Vertical stabilization .....	264	6.3.3.	Radiation effects .....	316
2.2.1.	Stability analysis .....	264	6.3.4.	Inorganic insulation .....	317
2.2.2.	Active coil system .....	273	6.3.5.	Conductors .....	317
2.2.3.	Benchmark calculations .....	281	6.3.6.	Experimental data – impact on INTOR reference designs .....	318
2.3.	Radial position control .....	283	6.4.	Fast pulse power supply technology – data base assessment ...	319
3.	Startup .....	287	6.4.1.	Fast pulse power supply technology – impact on INTOR reference design .....	319
3.1.	Electric and magnetic field penetration .....	288		References to Chapter V .....	319
3.1.1.	Electric field penetration .....	288		<b>VI. MAINTAINABILITY .....</b>	<b>321</b>
3.1.2.	Magnetic field penetration .....	291	1.	Introduction .....	321
3.2.	Parametric studies .....	291	1.1.	Background .....	321
4.	Plasma disruption effects .....	298	1.2.	Purpose of the study .....	323
4.1.	Computational models .....	298	1.3.	General requirements and considerations .....	323
4.2.	Induced currents .....	299	1.4.	Configuration parameters .....	325
4.3.	Induced forces .....	304	1.5.	Maintenance requirements and scenarios considered .....	325
4.4.	Induced voltages .....	307	1.5.1.	Personnel access maintenance considerations .....	325
4.5.	Benchmark calculations .....	308	1.5.2.	All-remote maintenance considerations .....	326
5.	Conclusions .....	309	1.5.3.	Miscellaneous assumptions common to both designs .....	326
5.1.	Plasma stabilization .....	309	2.	Assessment and analysis for the different maintenance concepts .....	327
5.2.	Startup .....	310	2.1.	Design requirements and assumptions for both maintenance concepts .....	327
5.3.	Disruptions .....	311	2.1.1.	Requirements and assumptions .....	327
5.4.	Design guidelines .....	311	2.1.2.	Tritium releases into the reactor hall from various sources .....	328
5.4.1.	Plasma vertical stabilization .....	311			
5.4.2.	Startup .....	312			
5.4.3.	Disruption .....	313			
6.	Data base assessment .....	313			
6.1.	INTOR design requirements .....	313			
6.2.	Analytical tools – data base assessment .....	314			
6.2.1.	Startup (distributed plasma current with motion and deformation) .....	314			
6.2.2.	Startup and disruption eddy current effects .....	314			
6.2.3.	Plasma vertical stability .....	314			

2.1.3.	Radiation source from coolant leakage .....	328	2.6.	Maintenance equipment .....	372
2.1.3.1.	Preliminary estimates of chronic leakage from INTOR water-coolant systems .....	328	2.6.1.	Maintenance equipment requirements .....	372
2.1.3.2.	Impact on personnel access .....	331	2.6.2.	Listing of maintenance equipment .....	374
2.1.4.	Radiation shielding .....	331	2.6.3.	Recovery of maintenance equipment in case of failure .....	376
2.1.4.1.	Shield requirements .....	331	3.	Comparison of the two concepts .....	378
2.1.4.2.	Radiation protection of the environment during operation and maintenance .....	333	3.1.	Basis of comparison .....	379
2.1.5.	Radiological guidelines and limits .....	333	3.2.	Maintenance equipment requirements .....	379
2.1.6.	Control of radioactive particulates .....	334	3.3.	Reactor availability .....	380
2.1.6.1.	Background .....	334	3.4.	Safety .....	380
2.1.6.2.	Impact on maintenance operations ....	334	3.5.	Flexibility of operations .....	380
2.2.	Tritium confinement and cleanup .....	335	3.6.	Costs .....	381
2.2.1.	Location and confinement boundaries for tritium and contaminated dust during operation and maintenance .....	335	3.7.	General conclusions .....	382
2.2.2.	Bakeout and pumpdown criteria .....	337	4.	Data base assessments for remote-handling technology .....	385
2.2.3.	Atmospheric tritium recovery .....	340	4.1.	INTOR design requirements .....	385
2.3.	Shielding requirements .....	343	4.2.	Data base assessment .....	385
2.3.1.	Radiation protection of the environment during operation and maintenance .....	343	4.2.1.	Computer-aided robotic design and simulation ....	386
2.3.2.	Shield optimization .....	345	4.2.2.	Manipulators and current robotics technology including heavy-duty manipulators, lifting and transport systems .....	387
2.3.3.	Problems of streaming through the divertor and RF launchers .....	348	4.2.3.	Cutting, welding, mechanical joining, electrical connecting and tooling systems .....	389
2.4.	Reactor configuration and facility layouts .....	353	4.2.4.	Sensing, lighting, viewing, leak detecting, testing and inspection systems .....	391
2.4.1.	All-remote configuration development .....	353	4.2.5.	Advanced computer-aided teleoperation, including artificial intelligence systems .....	392
2.4.2.	Reactor building layout .....	357	4.2.6.	Special equipment for teleoperation in hostile environment .....	393
2.4.3.	Hot cell and equipment storage .....	360	4.2.7.	Reliability, availability and maintainability data ....	394
2.4.4.	Tritium system building .....	361	4.3.	R and D programmes .....	394
2.5.	Maintenance scenarios and necessary time .....	361	4.4.	Impact on INTOR design concept .....	395
2.5.1.	Assumptions .....	361			
2.5.2.	Downtime and dose estimates for component replacement .....	362			
2.5.2.1.	Divertor module replacement .....	365			
2.5.2.2.	ICRH, ECRH and LHRH module replacement .....	366			
2.5.2.3.	Cryopump module replacement .....	366			
2.5.2.4.	Test module replacement .....	367			
2.5.2.5.	Torus sector replacement .....	367			
2.5.2.6.	TF coil replacement .....	367			
2.5.3.	Lifetime dose estimate and downtime for reactor cell maintenance .....	370			
2.5.4.	Comparison of downtime and exposure .....	371			
				References to Chapter VI	
				<b>VII. TECHNICAL BENEFIT OF PARTITIONING INTOR COMPONENT DESIGN AND FABRICATION .....</b>	<b>397</b>
			1.	Purpose and scope .....	397
			2.	Technical benefit definition .....	398
			3.	Assumptions and approaches .....	398
			3.1.	Assumptions .....	398
			3.1.1.	Reference organization scheme .....	398
			3.1.2.	Partitioning scenarios .....	399
			3.1.3.	Further common basis for evaluations .....	400

3.2.	Approaches .....	401	1.2.3.	Disruptions .....	473
3.2.1.	Cost evaluation methods .....	401	1.2.3.1.	Experimental status .....	473
3.2.1.1.	Cost evaluation (EC) .....	401	1.2.3.2.	Theory .....	475
3.2.1.2.	Cost evaluation (Japan) .....	404	1.2.3.3.	Comparison and conclusions .....	479
3.2.1.3.	Cost evaluation (US) .....	405	1.3.	R and D programmes .....	480
3.2.1.4.	Cost evaluation (USSR) .....	406	1.3.1.	Ongoing programmes and expected advances .....	480
3.2.2.	Schedule evaluation methods .....	407	1.3.2.	Additional R and D needs .....	482
3.2.2.1.	Schedule evaluation (EC) .....	407	1.4.	Impact on INTOR design .....	482
3.2.2.2.	Schedule evaluation (Japan) .....	409	2.	Confinement .....	485
3.2.2.3.	Schedule evaluation (US) .....	409	2.1.	Design assumptions and parameters (Phase Two A Part 1) ....	485
3.2.2.4.	Schedule evaluation (USSR) .....	409	2.2.	Data base .....	485
3.2.3.	Consideration of additional manpower .....	409	2.2.1.	Energy confinement .....	485
3.2.4.	Quantification of technical benefit .....	411	2.2.1.1.	Experimental status .....	486
3.3.	Information input (summary) .....	413	2.2.1.2.	Semi-empirical transport analysis .....	504
3.3.1.	Components/subsystems questionnaires .....	413	2.2.1.3.	Comparisons and discussions .....	505
3.3.2.	Questionnaires on project planning/implementation and quality production .....	413	2.2.1.4.	Conclusions of data base assessment ....	506
4.	Evaluation results .....	415	2.2.2.	Particle confinement .....	507
4.1.	Cost .....	415	2.2.2.1.	Experimental status .....	509
4.1.1.	EC evaluation .....	415	2.2.2.2.	Status of theory .....	519
4.1.2.	Japanese evaluation .....	415	2.2.2.3.	Conclusions .....	519
4.1.3.	US evaluation .....	422	2.2.3.	Momentum confinement and plasma rotation .....	519
4.1.4.	USSR evaluation .....	422	2.2.3.1.	Experimental status .....	519
4.2.	Schedule .....	426	2.2.3.2.	Theory .....	521
4.3.	Benefit .....	426	2.2.3.3.	Comparison and conclusions .....	522
5.	Other large projects' experience .....	428	2.3.	R and D programme .....	522
6.	Conclusions .....	429	2.3.1.	Ongoing programmes and expected advances .....	522
	References to Chapter VII .....	430	2.3.2.	Additional R and D requirements .....	523
	Appendix to Chapter VII: Tables VII-A1 to VII-A10 .....	431	2.4.	Impact on INTOR design .....	523
<b>VIII. PHYSICS</b>	.....	453	3.	Neutral-beam heating and current drive .....	524
1.	Stability limits .....	453	3.1.	INTOR design assumptions and parameters (Phase Two A Part 1) .....	524
1.1.	INTOR design assumptions and parameters (Phase Two A Part 1) .....	453	3.2.	Data base .....	524
1.2.	Data base .....	456	3.2.1.	Neutral-beam heating .....	524
1.2.1.	Beta limits .....	456	3.2.1.1.	Experimental status .....	524
1.2.1.1.	Experimental status .....	456	3.2.1.2.	Theory .....	526
1.2.1.2.	Theory .....	460	3.2.1.3.	Comparison and conclusions .....	526
1.2.1.3.	Comparisons and conclusions .....	465	3.2.2.	Neutral-beam current drive .....	527
1.2.2.	Density limits .....	467	3.2.2.1.	Experimental status .....	527
1.2.2.1.	Experimental status .....	467	3.2.2.2.	Theory .....	527
1.2.2.2.	Theory .....	472	3.2.2.3.	Comparison and conclusions .....	528
1.2.2.3.	Comparisons and conclusions .....	472	3.3.	R and D programmes .....	528
			3.3.1.	Ongoing programmes and expected advances .....	528
			3.3.2.	Additional R and D needs .....	528
			3.4.	Impact on INTOR design .....	529
			4.	Operation scenarios .....	529
			4.1.	INTOR design assumptions and parameters (Phase Two A Part 1) .....	529

4.2.	Data base .....	530	6.3.2.4.	Tritium qualification of diagnostic vacuum equipment .....	548
4.2.1.	Experimental results .....	530	6.3.2.5.	Diagnostics reliability .....	548
4.2.2.	Theory .....	531	6.3.2.6.	Penetration of the radiation shielding ....	549
4.2.3.	Comparison and conclusions .....	531	6.4.	Impact on INTOR design .....	552
4.3.	R and D programme .....	532	6.4.1.	Ports and penetrations in the shield .....	552
4.3.1.	Ongoing programme and expected advances .....	532	6.4.2.	Port allocations on INTOR .....	553
4.3.2.	Additional R and D needs .....	532	6.4.3.	Diagnostic instrumentation allocation .....	554
4.4.	Impact on INTOR design .....	532	6.4.4.	Conclusions .....	554
5.	Burning plasma .....	533		References to Chapter VIII .....	554
5.1.	INTOR design assumptions and parameters (Phase Two A Part 1) .....	533			
5.2.	Data base .....	533			
5.2.1.	Physics of burning plasmas .....	533			
5.2.1.1.	Experimental status .....	533			
5.2.1.2.	Theory .....	533			
5.2.1.3.	Comparison and conclusions .....	535			
5.2.2.	Burn temperature control methods .....	535			
5.2.2.1.	Experimental status .....	535			
5.2.2.2.	Theory .....	536			
5.2.2.3.	Comparison and conclusions .....	538			
5.3.	R and D requirements .....	538			
5.3.1.	Ongoing programmes and expected advances .....	538			
5.3.2.	Additional R and D needs .....	539			
5.4.	Impact on INTOR design .....	539			
6.	Plasma diagnostics .....	539			
6.1.	Introduction .....	539	1.	Introduction .....	557
6.2.	Data base .....	540	2.	Systems engineering .....	557
6.2.1.	Plasma parameters .....	540	2.1.	Summary of INTOR requirements .....	558
6.2.1.1.	Electromagnetic measurements .....	542	2.1.1.	Overall optimization codes.....	558
6.2.1.2.	Electron density .....	542	2.1.2.	Subsystem codes .....	558
6.2.1.3.	Electron temperature .....	542	2.1.3.	Cost data base .....	558
6.2.1.4.	Ion temperature .....	542	2.1.4.	Computer-aided design systems .....	559
6.2.1.5.	Radiative losses .....	543	2.2.	Analytical tools .....	559
6.2.1.6.	Impurity concentration .....	543	2.2.1.	Data base .....	559
6.2.1.7.	Runaway electrons .....	543	2.2.2.	R and D requirements .....	565
6.2.1.8.	Hard-X-ray and neutron radiation .....	543	2.2.3.	Impact on INTOR design .....	565
6.2.1.9.	Concentration of helium ions .....	545	2.3.	Systems cost data base .....	565
6.2.2.	Discharge control .....	545	2.3.1.	Data base .....	565
6.3.	R and D programmes .....	545	2.3.2.	R and D requirements .....	569
6.3.1.	Ongoing programmes and expected advances .....	545	2.3.3.	Impact on INTOR design .....	569
6.3.2.	Additional R and D needs .....	545	2.4.	Design tools (computer-aided design and computer graphic systems) .....	569
6.3.2.1.	Development of diagnostics applicable in INTOR .....	545	2.4.1.	Data base .....	569
6.3.2.2.	Radiation hardness .....	546	2.4.2.	R and D requirements .....	570
6.3.2.3.	RF noise shielding for diagnostic instrumentation .....	548	2.4.3.	Impact on INTOR design .....	570
			3.	Magnets .....	570
			3.1.	Summary of magnet system design requirements .....	570
			3.2.	Structures .....	573
			3.2.1.	Mechanical characteristics .....	573
			3.2.2.	Radiation effects .....	575
			3.2.3.	Quality control techniques .....	576
			3.2.4.	Impact on INTOR design .....	576

3.3.	Conductors .....	576	5.2.	Negative-ion-based NBI .....	598
3.3.1.	Critical current characteristics.....	576	5.2.1.	INTOR requirements .....	598
3.3.2.	Stability characteristics .....	577	5.2.2.	Data base assessment.....	599
3.3.3.	Heat transfer characteristics .....	579	5.2.3.	R and D programme .....	599
3.3.4.	Analytical tools .....	580	5.2.4.	Impact on INTOR design .....	600
3.3.5.	Manufacturing technology .....	582	6.	Pellet injection .....	600
3.3.6.	Radiation effects .....	583	6.1.	INTOR requirement.....	600
3.3.7.	Impact on INTOR design – conductors .....	584	6.1.1.	Pellet composition .....	601
3.4.	Insulation .....	584	6.1.2.	Pellet velocity .....	601
3.4.1.	Data base assessment .....	584	6.2.	Data base assessment.....	601
3.4.2.	R and D requirements .....	586	6.3.	Impact on INTOR design .....	602
3.4.3.	Impact on INTOR design .....	586	7.	Radiation-hardened diagnostics and instrumentation .....	603
3.5.	Refrigeration.....	586	7.1.	INTOR requirements .....	603
3.5.1.	Data base assessment – cryogenic components .....	586	7.2.	Data base assessment.....	603
3.5.2.	R and D requirements – cryogenic components .....	587	7.3.	R and D programmes .....	603
3.5.3.	Impact on design – cryogenic components .....	587	7.4.	Impact on INTOR design .....	606
3.5.4.	Data base assessment – analytical tools .....	587		References to Chapter IX.....	606
3.5.5.	R and D programmes – analytical tools .....	589			
3.5.6.	Impact on INTOR design – analytical tools.....	589	<b>X.</b>	<b>NUCLEAR.....</b>	<b>609</b>
3.6.	Demonstration coil projects .....	589	1.	Blanket data base assessment .....	609
3.6.1.	Data base assessment – poloidal field coils .....	589	1.1.	Summary of INTOR design requirements .....	609
3.6.2.	R and D projects – poloidal field coils.....	589	1.1.1.	Blanket design options .....	609
3.6.3.	Impact – poloidal field coils .....	590	1.1.2.	Blanket design parameters.....	610
3.6.4.	Data base assessment – toroidal field coils .....	590	1.2.	Blanket issues.....	610
3.6.5.	R and D requirements – toroidal field coils .....	590	1.2.1.	Neutronics and tritium breeding .....	610
3.6.6.	Impact – toroidal field coils .....	591	1.2.1.1.	General remarks .....	610
4.	Vacuum enclosure and vacuum technology .....	591	1.2.1.2.	Tritium breeding requirements.....	611
4.1.	Summary of INTOR Phase Two A design requirements .....	591	1.2.1.3.	Nuclear data availability .....	611
4.1.1.	Vacuum enclosure requirements .....	591	1.2.1.4.	Current status of nuclear data .....	612
4.1.2.	Vacuum technology requirements .....	592	1.2.1.5.	Neutronics methods and codes .....	614
4.2.	Vacuum enclosure .....	593	1.2.2.	Solid breeder blankets .....	615
4.2.1.	Data base.....	593	1.2.2.1.	Material data .....	615
4.2.2.	R and D programmes .....	594	1.2.2.2.	Fabrication data .....	618
4.2.3.	Impact on INTOR reference design .....	594	1.2.2.3.	Tritium recovery .....	620
4.3.	Vacuum technology .....	594	1.2.2.4.	Neutron multipliers – Be, Pb .....	625
4.4.	R and D programmes .....	595	1.2.2.5.	Tritium release and recovery models .....	626
5.	Heating system (NBI) .....	596	1.2.3.	Liquid breeder blankets .....	629
5.1.	Positive-ion-based NBI .....	596	1.2.3.1.	Materials data .....	629
5.1.1.	INTOR requirements .....	596	1.2.3.2.	Data on liquid-metal corrosion .....	629
5.1.2.	Data base assessment.....	596	1.2.3.3.	Data on MHD effects in liquid metals .....	635
5.1.3.	R and D programmes .....	597			
5.1.4.	Impact on INTOR design .....	598			

1.2.3.4.	Tritium solubility and recovery from lithium and LiPb .....	636	3.	Tritium system data assessment.....	677
1.2.4.	Models and codes .....	637	3.1.	Summary of INTOR Phase Two A design requirements .....	677
	Test module instrumentation requirements.....	638	3.1.1.	Major subsystems .....	677
	1.2.4.1. Dosimetry .....	638	3.1.2.	Design parameters .....	678
	1.2.4.2. Thermal hydraulics and thermomechanics .....	641	3.2.	Data base assessment .....	678
1.2.5.	Ceramic insulators .....	643	3.2.1.	Tritium properties.....	678
	1.2.5.1. Base properties of ceramics .....	643	3.2.2.	Tritium permeation into the coolant.....	680
	1.2.5.2. Radiation effects on properties of ceramics .....	644	3.2.3.	Tritium-processing techniques.....	682
	1.2.5.3. Fabrication of ceramic components .....	646	3.2.4.	Tritium transportation .....	685
1.3.	R and D programmes .....	647	3.2.5.	Models and codes .....	686
1.3.1.	Neutronics R and D programmes .....	647	3.3.	R and D programmes .....	687
	1.3.1.1. Ongoing programmes .....	647	3.3.1.	Ongoing programmes and test facilities .....	687
	1.3.1.2. Test facilities – integral experiments for blankets and cross-section measurements .....	650	3.3.2.	Required new programmes .....	689
	1.3.1.3. Required R and D programmes .....	651	3.3.3.	Impact of new tritium data/results on INTOR reference design .....	689
1.3.2.	Solid breeder programmes .....	653	3.3.4.	Impact of change in the breeding ratio.....	689
	1.3.2.1. Ongoing programmes .....	653	4.	Safely and environmental data base assessment.....	690
	1.3.2.2. Test facilities .....	655	4.1.	Summary of INTOR Phase Two A design requirements .....	690
	1.3.2.3. Required new programmes.....	655	4.1.1.	Dose limits .....	690
1.3.3.	Liquid breeder programmes .....	655	4.1.2.	Doses in normal operation .....	690
	1.3.3.1. Ongoing programmes .....	655	4.1.3.	Limits for accidental releases of radioactivity .....	690
	1.3.3.2. Test facilities .....	657	4.2.	Safety and environmental data base .....	691
	1.3.3.3. Required new programmes .....	658	4.2.1.	Safety-related criteria.....	691
1.4.	Impact of new blanket data on INTOR reference design.....	659	4.2.1.1.	Allowable tritium release to the environment.....	691
	Shield data base assessment.....	659	4.2.1.2.	Maximum tritium release in accident conditions .....	691
2.1.	Summary on INTOR Phase Two A design requirements .....	659	4.2.1.3.	Radioactive products .....	691
	2.1.1. Design options .....	659	4.2.1.4.	Magnetic fields .....	692
	2.1.2. Design goals .....	660	4.2.1.5.	Radiofrequency radiation .....	692
2.2.	Data base assessment.....	660	4.2.1.6.	Abnormal events .....	692
	2.2.1. Protection criteria .....	660	4.2.1.7.	Criteria for waste disposal .....	692
	2.2.2. Shielding and radioactivity cross-sections .....	662	4.2.2.	Radioactive source term .....	693
2.3.	Current R and D programmes and test facilities .....	665	4.2.2.1.	Tritium inventory, tritium storage, tritium permeation.....	693
	2.3.1. Cross-sections for transport calculations .....	666	4.2.2.2.	Coolant leakage level and maximum allowable tritium concentration in the coolant.....	693
	2.3.2. Activation data .....	668	4.2.3.	Radioactive products in air and coolant .....	693
	2.3.3. Integral shielding experiments.....	669	4.2.4.	Radioactive waste considerations .....	693
	2.3.4. Required new programmes .....	674	4.3.	R and D programmes .....	694
2.4.	Impact of new shield data/results on INTOR reference design.....	676	4.3.1.	Ongoing programmes .....	694
			4.3.1.1.	USA .....	694

4.3.1.2. Japan .....	695	4.2. TF coil design .....	742
4.3.1.3. Europe .....	695	4.2.1. Ripple requirement .....	742
4.3.1.4. USSR .....	696	4.2.2. TF coil thickness .....	744
4.3.2. Test facilities.....	696	4.3. PF system .....	745
4.3.3. Required new programmes .....	696	4.4. Vacuum boundary .....	746
References to Chapter X .....	697	4.5. Torus system.....	746
<b>XI. INTOR CONCEPT EVOLUTION .....</b>	<b>699</b>	4.6. Radial build .....	747
1. Role of INTOR in the fusion programme .....	700	4.7. Impurity control .....	747
2. INTOR objectives .....	701	5. Assembly and maintenance .....	747
3. INTOR concept evolution.....	702	5.1. Introduction .....	747
References to Chapter XI.....	712	5.2. Assembly and maintenance approach.....	748
<b>XII. DESIGN CONCEPT .....</b>	<b>713</b>	5.2.1. Toroidal magnetic field coil design – access requirements .....	748
0. Introduction .....	713	5.2.2. Poloidal magnetic field coil system .....	749
1. Design specifications .....	714	5.2.3. Vertical stabilization coils .....	750
2. Physics basis .....	714	5.2.4. Combined cryogenic and torus vacuum chamber topology .....	751
2.1. Beta .....	714	5.2.5. Torus modularization and segmentation .....	753
2.2. Density limit .....	719	5.2.6. Impurity control .....	753
2.3. Disruptions .....	719	5.2.7. Structural support system .....	755
2.4. Confinement data base.....	727	5.2.8. Assembly .....	756
2.5. Burning-plasma considerations .....	727	5.3. Alternative assembly and maintenance approach.....	756
2.6. Plasma diagnostics.....	729	5.3.1. Assembly and vertical access .....	759
3. Trade studies .....	729	6. RF heating and current drive .....	761
3.1. Reduction in device size.....	731	6.1. Ion cyclotron heating system .....	761
3.1.1. Inboard shield thickness.....	731	6.2. Lower hybrid current ramp-up/transformer recharge system .....	762
3.1.2. TF coil current density .....	731	6.3. Electron cyclotron startup system .....	763
3.1.3. Inboard scrape-off region .....	732	7. Operating scenarios .....	764
3.1.4. OH solenoid design .....	733	7.1. Inductive operating scenario .....	766
3.1.5. Radial build .....	733	7.2. Operating scenario including RF current drive .....	768
3.2. Startup capability .....	734	7.2.1. Physics considerations of non-inductive operation ..	768
3.3. OH swing and plasma heating time .....	735	7.2.2. Engineering considerations associated with non-inductive current ramp-up and transformer recharge .....	769
3.3.1. OH swing time .....	735	8. Vertical position stabilization .....	771
3.3.2. Plasma heating time .....	735	9. Magnets .....	775
3.4. Safety factor .....	736	9.1. Introduction .....	775
3.5. Variations of beta.....	739	9.2. Toroidal field coil system .....	776
4. Configuration.....	739	9.3. Poloidal field coil system .....	779
4.1. Introduction .....	739	9.4. Active vertical position control coil system .....	779
4.1.1. Objectives .....	739	9.5. TF coil power conversion and protection .....	780
4.1.2. Design requirements.....	740	9.6. PF coil power conversion and protection .....	781
		9.7. Cryostat and cryogenic system .....	782

10. Impurity control .....	783	XIV. ADMINISTRATIVE APPENDICES .....	825
10.1. Collector plate studies.....	783	1. INTOR Phase Two A Part 2 Workshop Sessions .....	825
10.2. Reduced-channel-length divertor.....	789	2. European INTOR home-base organization .....	825
11. First wall.....	790	2.1. Euratom INTOR Workshop Team.....	825
12. Tritium-producing blanket .....	792	Workshop participants and attendees .....	825
13. Tritium and vacuum .....	794	INTOR/NET Steering Group.....	825
13.1. Tritium system.....	794	Contributors to individual chapters.....	826
13.2. Vacuum system.....	795	Organizational index .....	829
14. Radiation shield .....	796	Publications during Phase Two A Part 2 .....	830
14.1. Toroidal field coil protection .....	797	3. Japan INTOR Workshop Team .....	831
14.2. Shield thickness and composition .....	798	Workshop participants and attendees .....	831
14.3. Conclusions.....	801	Contributors to individual chapters.....	831
15. Facilities .....	802	Organizational index .....	836
15.1. Site criteria .....	802	4. USA INTOR Workshop Team .....	836
15.2. Facility layout.....	802	Workshop participants and attendees .....	836
16. Cost evaluation.....	807	Contributors to individual chapters.....	836
16.1. Direct capital costs.....	807	Organizational index .....	842
16.2. Indirect capital costs .....	809	5. USSR INTOR Workshop Team .....	843
16.3. Operation costs .....	809	Workshop participants and attendees .....	843
References to Chapter XII.....	809	Contributors to individual chapters.....	843
		Organizational index .....	849
 XIII. OPERATION AND TEST PROGRAMME .....	811		
1. Role of INTOR tests .....	811		
2. Operational requirements.....	812		
2.1. Fluence requirements for structural materials radiation damage tests.....	813		
2.2. Blanket testing requirements.....	814		
2.3. Long-term operation component reliability .....	818		
3. Operation schedule .....	818		
4. Test programme .....	819		
4.1. Plasma operation in Stage I and plasma experiments.....	820		
4.2. Plasma engineering tests .....	820		
4.3. Blanket engineering tests.....	820		
4.4. Materials testing: bulk properties .....	821		
4.5. Materials testing: surface effects .....	821		
4.6. Surveillance tests.....	822		
4.7. Nuclear tests .....	822		
4.8. Electricity generation.....	822		
References to Chapter XIII.....	823		