ENGINEERING SCIENCES

Programme Code: ENGG04

Programme Outcome:

The courses in engineering sciences aim to provide the research scholars a broad overview of the subjects which are relevant for their research programs in fast reactor technology. The students are equipped with in depth knowledge of skill set required for research work. The courses cover advanced topics in the areas of Fuel Cycle, Nuclear Power Plant Technology, Radiation Safety, Health Physics, Material Science, Reactor Systems, Reactor Physics, Computation and Simulation which are useful for the students to understand their research areas and carry out their experimental and theoretical work. Th courses are deigned to help students understand the various aspects of their field of research, foster a sense of enquiry, independent thinking about the solutions to the problems that define their areas of research

DETAILED COURSE STRUCTURE

Foundation Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	EM	Engineering Mathematics	35	2
2.	MM	Materials and Metallurgy	25	1
3.	RP	Fast Reactor Physics and Shielding	35	2
4.	HP	Health Physics and Radiological Safety	25(15 T+10 L)	1
5.	NR	Nuclear Reactors	50	3
6.	RE	Reactor Engineering	40	2
		FOUNDATION TOTAL	**210**	**11**

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	CE1	Nuclear Chemical Engineering	35	2
2.	CE2	Chemical Engineering Thermodynamics	40	2
3.	CE3	Transport Phenomena	40	2
4.	CE4	Multi Phase Flow Systems	40	2
5.	CE5	Code Design for Pressure Vessels and Piping	25	1
6.	CE6	Computational Fluid Dynamics & Heat Transfer	40	2
7.	CE7	Advanced Chemical Reaction Engineering	25	1
		CORE TOTAL	**245**	**12**

Electives (any one)					
Sr. No	**Course Code**	**Subject Title**	**Hours**		**Credits**
			(T)	**(L)**	
1.	CE-EL3	Artificial Intelligence Methods and Applications	30	-	2
2.	CE8	Process Analysis and Control	25	-	1
3.	CE9	Advanced Mass Transfer	25	-	1
		ELECTIVES TOTAL	**80**	**-**	**4**

FOUNDATION COURSES COORDINATOR

Course	Coordinators	Contact
EM: Engineering Mathematics	Dr. K. Natesan	22109/22856,natesan@igcar.gov.in
	Dr. V. Satish Kumar	26919/26977,vsatish@igcar.gov.in
MM: Materials and Metallurgy	Dr. Vani Shankar	21147/22805,vani@igcar.gov.in
RP: Fast Reactor Physics and Shielding	Shri Rajeev Ranjan Prasad	22737,rajeevphy@igcar.gov.in
HP: Health Physics and Radiological Safety	Dr. S. Chandrasekaran	23556.schand@igcar.gov.in
NR: Nuclear Reactors	Shri D.Nagasivayya	21232,dnsiva@igcar.gov.in
RE: Reactor Engineering	Shri Sriramachandra Aithal	22468/22605,saithal@igcar.gov.in

CORE COURSES COORDINATOR

Course	Coordinators	Contact
CE1: Nuclear Chemical Engineering	Dr. K. A. Venkatesan	22631/26857, kavenkat@igcar.gov.in
CE2: Chemical Engineering Thermodynamics	Dr. Vidhya Sundararajan	22474/22454, vidya@igcar.gov.in
CE3: Transport Phenomena	Shri Sourabh Agarwal	22737/22268, sourabh@igcar.gov.in
CE4: Multiphase Flow System	Dr. K. A. Venkatesan	22631/26857, kavenkat@igcar.gov.in
CE5: Code Design for Pressure Vessels and Piping	Shri S. D. Sajish	22795/22452, sajish@igcar.gov.in
CE6: Computational Fluid Dynamics and Heat Transfer	Shri Rajendrakumar	22313/21334, mrk@igcar.gov.in
	Dr. K. A. Venkatesan	22631/26857, kavenkat@igcar.gov.in
CE7: Advanced Chemical Reaction Engineering	Shri J. Kodandaraman	26962/27263, jkr@igcar.gov.in

ELECTIVES COURSES COORDINATOR

Course	Coordinators	Contact
CE-EL3: Artificial Intelligence Methods and Applications	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
CE8: Process Analysis and Dynamics	Dr. K. A. Venkatesan	22631/26857, kavenkat@igcar.gov.in
CE9: Advanced Mass Transfer	Dr. K. A. Venkatesan	22631/26857, kavenkat@igcar.gov.in

FOUNDATION COURSES

EM: Engineering Mathematics (35 Lecture Hrs)

Coordinators: Dr. K Natesan(natesan@igcar.gov.in),
Dr. V. Satish Kumar(vsatish@igcar.gov.in)

Course Details:

- Computer arithmetic and errors . Types of errors, error estimates and its propagation, Data analysis : Difference tables, Interpolation methods of Lagrange and Hermite, Chebyshev polynomials and Pade's approximation with rational functions. Numerical differentiation of interpolating polynomials. Numerical Integration : Trapezoidal, Monte-Carlo and Gaussian Quadrature methods Solution of algebric and transcendental equations, Newton-Raphson method, Graffe's root squaring method; Data approximation by method of least square, curve fitting.
- Linear vector space and subspaces, Basis, Gram-Schmidt orthogonalization, Linear system of equations: LU decomposition, Cholesky factorization and Gauss-Jordan technique. Iterative techniques using the methods of Jacobi, Gauss-Seidel and over relaxation. Convergence criteria and error estimation. Matrix inverse, Ill conditioned and sparse matrices. Bilinear forms, Principal axes transformation and eigen values, Determination of eigen values and eigen vectors. LU and QR algorithms, Singular matrices and singular value decomposition.
- Ordinary differential equations, Different types of differential equations, Lipschitz theorem and conditions for existence and uniqueness of solutions, Numerical methods for solving differential equations. Method of Euler, Adams and Runge Kutta, Predictor corrector method, Solving stiff equations.
- Probability and Statistics:Probability and Random variables, Binomial, Poisson and Normal distributions, Moments of a distribution, Counting experiments Estimation of model parameters, Confidence intervals, Testing of hypotheses, Goodness of fit, Chi-square test.
- Integral Transforms: Laplace transform, Linearity of LT, LT of derivatives and integrals, Solution of differential equations using LT, Response of electric circuits, Response of damped oscillator to a square wave, Differentiation and integration of LT.Periodic functions, Fourier series representation of functions, Even and odd functions, Determination of coefficients, Fourier integrals. Data compression, Hauffman coding and wavelet transforms.
- Partial Differential Equations, Finite difference method in one and two dimensions, Solution of steady and transient heat conduction and diffusion equations.
- Finite element method, Energy Theorem and integral equations, Weighted residual approximations, Point and subdomain collocation. Galerkin method, Variational principles and Lagrange multipliers. B-splines,Bezier curves, Response surface method, different levels of factorial design.

Course Outcomes:

Students will be able to apply computer arithmetic, error analysis, interpolation methods (Lagrange and Hermite), Chebyshev polynomials, and numerical integration techniques to engineering problems. They will analyze linear vector spaces, LU/QR decomposition, eigenvalue problems, differential equations, probability distributions, Laplace/Fourier transforms, PDEs, and finite element methods for mathematical modeling and computation.

References:

1. Davis, H. T. and Thompson, K., Linear Algebra and Linear Operators in Engineering: with Applications in Mathematica, Academic Press, 2000.
2. Chapra, S.C. and Canale, R.P., Numerical Methods for Engineers, McGraw-Hill, 1985.
3. R. L. Burden and J. D. Faires, Numerical Analysis, 6th ed., PWS-Kent Publishing, 1997.
4. Krishnamurthy, E. V., Computer based numerical algorithms, East West Press, 1976.
5. Gupta, S.K., Numerical methods for Engineers, Wiley (1995).
6. Press, W.H.; Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., Numerical Recipes in Fortran (or C), Cambridge University Press (1992).
7. Scarborough, J. B. Numerical Mathematical Analysis, Oxford and IBH Publishers, 1968.

MM: Materials and Metallurgy (25 Lecture Hrs)

Coordinators: Dr. Vani Shankar
(vani@igcar.gov.in)

Course Details:

- Classification of Materials: Structure, Ferrous and non-Ferrous metals, Polymers, Ceramics, Composites, Electronic materials, Nano-structured materials.
- Selection of Materials: Classification of carbon steel, low alloy, carbon molybdenum, ferritic, austenitic and martenistic stainless steel. Selection and application of advanced alloys, stainless steels, Cr-Mo steels, Ti-alloys
- Heat Treatment and Mechanical Testing of materials including standards and specifications: Mechanical properties of materials & their evaluations as per ASTM or equivalent standards, tension, hardness, creep, fatigue (low & high cycle) & impact toughness tests.
- Metal Forming, Welding Science & Technology: Metal fabrication technologies, rolling, forging, extrusion, deep drawing and introduction to material modelling. Welding metallurgy for stainless steels, ferritic steels, dissimilar metal welds and Ti-alloys, hard-facing and repair welding.
- Metallographic Examination: Experimental techniques for characterization of microstructure (Optical, TEM/SEM and microscopic techniques) specimen preparation and evaluation of microstructure of different materials.
- Corrosion: Galvanic, Uniform, Crevice, Stress corrosion cracking, Corrosion fatigue, Corrosion fast reactors and re-processing plants, Corrosion test methods and standards.
- Non-destructive evaluation techniques for materials and components: Visual, LPT, MPT, UT, Eddy current, X-ray Radiography, Neutron, Gamma ray etc. for quality assurance and in-service inspection.
- Nuclear Fuels: Production, fabrication, properties and application of nuclear fuels (metallic fuels, ceramic fuels (oxide, mixed oxide, mixed carbide)) and heavy water. Radiation damage and post irradiation examination of core materials.

Course Outcomes:

Students will understand classification and selection of engineering materials including carbon steels, stainless steels, Ti-alloys, polymers, ceramics, composites, and nuclear fuels. They will evaluate materials using heat treatment, mechanical testing (creep, fatigue, hardness, impact), metallographic examination, corrosion studies, welding metallurgy, and non-destructive evaluation techniques.

References:

1. Introduction to Materials Science for Engineers - James Shackelford
2. Physical Metallurgy Principles & Practice - V.Raghavan
3. Introduction to Solids - L.V.Azaroff
4. Structure and Properties of Materials - Wulff Series, Wiley Eastern, New Delhi
5. Materials in Nuclear Application - C.K.Gupta
6. Nuclear Chemical Engineering - Benedict and Pigford
7. Physical Metallurgy, Reed – Hill
8. Heat treatment of steel – Avener
9. Introduction to Solid State Physics - Charles Kittel (Wiley Eastern)
10. Physical Metallurgy: Principles and Practice - V. Raghavan (Prentice Hall)
11. The Physics and Chemistry of Materials - Joel Gersten and Fiedenick Smith (Wiley, Canada)
12. Fundamentals of Materials Science and Engineering - D. Callister (Wiley, Europe)

RP: Fast Reactor Physics and Shielding (35 Lecture Hrs)

Coordinators: Shri Rajeev Ranjan Prasad (rajeevphy@igcar.ac.in)

Course Details:

- **NUCLEAR THEORY BASICS**

  - Properties of Nuclei: Size, shape and density of the nucleus, nuclear forces, nuclear structure, binding energy, stability of nucleus, radioactivity
  - Fission Process: Spontaneous and induced fission, liquid drop model, fission neutrons, delayed neutrons, fission gammas, fission products, fission product yield, FP mass asymmetry, formation and removal of FPs in a reactor
  - Concept of Nuclear Reactor: Fission energy, fission rate and reactor power, energy balance, fissile, fertile and fissionable materials, reactor materials: fuel, coolant, structure, control and shield, fission product activity after shutdown – decay heat, types of reactors
  - Interaction of Neutrons with Matter :Production of neutrons, elastic and inelastic scattering, radiative capture and their significance in reactors, production of photo neutrons, transmutation
  - Concept Cross-section :Microscopic and macroscopic cross-section, mean free path, Maxwell-Boltzmann distribution and its departure, structural changes caused by neutron reactions
  - Variation of Cross-section with Energy: Fast, resonance and thermal ranges, 1/v law of neutron cross-section, resonance absorption, Breit-Wigner formula, Doppler effect Capture to fission ratio, Eta vs E curve, conversion and breeding concepts, Thorium utilization

- **BASIC REACTOR PHYSICS-STATIC**

  - Diffusion of Neutrons: Fick's law and its validity, steady state neutron diffusion equation, concepts of neutron flux and current, interface conditions, diffusion coefficient, diffusion length and extrapolation distance
  - Chain Reaction :Four factor formula, conceptual treatment of diffusion of one group of neutrons in non multiplying and multiplying media, infinite and effective multiplication factors, bare homogeneous reactor concepts, material and geometrical buckling, sub criticality and super criticality, critical mass, non leakage probabilities in bare homogeneous cores, neutron cycle and life time in finite reactor
  - Slowing Down Process: Neutron Slowing down, slowing down power and moderating ratio of moderators, slowing down with spatial migration, Fermi age concepts, migration length, multi zone reactors, ideas of reflectors/blankets, reflector savings, form factor

- **TIME DEPENDENCE**

  - Reactor Kinetics: Time dependent neutron diffusion equation, one group kinetic equation, role of delayed neutrons, prompt neutron life time, point kinetic model to illustrate importance of delayed neutrons, reactor period, reactivity and its units
  - Core Burnup and Neutron Poisons: Burnup equations including fission products, Xenon and Samarium poisons, Xenon loads (operating and post shut down), variation of Xenon load with power and enrichment, Xenon oscillations and their control

- Reactivity Coefficients and Reactor Experiments: Temperature and void coefficients of reactivity, their relevance to reactor safety Techniques to control reactors, typical reactivity balance, long term burnup, fuel management, reactor control system – requirements of physics aspects, reactor shutdown mechanisms and neutron monitoring during operation and shut down Approach to criticality, physics measurements and calibrations/validations

- **FAST BREEDER REACTORS**

- Introduction: Fast reactors as breeders, comparison of fast and thermal reactors, types of fast reactor, role of fast reactors in Indian nuclear power program
- FBR Neutronics: Neutron spectrum, reaction cross-section, core characteristics, blanket characteristics, breeding potential, breeding ratio and breeding gain, doubling time, Multigroup diffusion theory methods and summary of steady state computational methods for FBR Effective delayed neutron fraction and prompt neutron life time, fuel expansion and bowing, sodium void reactivity effect, Doppler reactivity effect, long term reactivity effect - in FBR
- FBR Core Design: General features of FBR core, specific power, linear rating, burnup, fluence, requirement and choice of core materials (fuel, coolant and structural materials), test reactors, commercial fast reactors, pin diameter, core height/diameter ratio, blanket thickness
- Salient physics aspects of FBTR and PFBR
- Reactor Shielding: Source of various neutron & Gamma radiation within the reactor system; Attenuation of neutrons & gamma rays; Dose rates for gamma rays for various source geometries; Buildup factors for homogeneous & multiple layer shields; Removal diffusion theory for neutron attenuation; coolant activation, heat generation. Streaming of radiation through gaps & void in the shield; description of various shielding arrangements of Indian reactors

Course Outcomes:

Students will understand nuclear structure, fission process, neutron interaction, cross-section behavior, and neutron diffusion theory in reactor systems. They will analyze reactor kinetics, burnup, delayed neutrons, breeding ratio, multigroup diffusion theory, sodium void and Doppler reactivity effects, and design radiation shielding using neutron and gamma attenuation concepts.

References:

1. S. Glasstone and S. Sesonske, Nuclear Reactor Engineering, Van Nostrand, 1963.
2. S. Glasstone and M.C. Edlund, Elements of Nuclear Reactor Theory, Van Nostrand, 1952.
3. J. R. Lamarsh, Introduction to Nuclear Engineering, Addision Wesley, NY, 1960.
4. M. El-Wakil, Nuclear Power Engineering, McGraw-Hill
5. P.P. Zweifel, Reactor Physics, McGraw-Hill, 1973.
6. Weston M. Stacy, Nuclear Reactor Physics, John Wiley & Sons, Inc. 7. A.E. Walter & A.B. Reynolds, Fast Breeder Reactors, Pergamon Press.

HP: Health Physics & Radiological Safety (25 Lecture Hrs)

Coordinators: Dr. S. Chandrasekaran
(schand@igcar.ac.in)

Course Details:

- Introduction: Radiation sources: Natural and Induced radioactive sources, units of radioactivity, half-life and decay constant, specific activity. Basic interaction mechanism of a) alpha b) Beta c) Gamma/X-rays d) Neutrons with matter. Definition of various dosimetric terms (exposure, absorbed/equivalent/effective dose, concept of radiation/tissue weighting factors and their importance (SI units & new units). Concepts of Exposure measurement: Free air and Air wall chambers, Exposure-dose relationship, Bragg-Gray principle.
- Biological effects of Radiation: Human body: Cells, tissues and organs, structure of cell, cellular effects. Factors, which influence the damage of cell. Interaction of radiation with biological matter. Radiation effects: stochastic and deterministic. Acute and delayed effects. Types of exposure (natural, occupational, medical and public).
- Radiation Protection and Regulations:
  - Importance of radiation protection program in DAE, Atomic Energy act, National and International regulatory bodies, their role and responsibilities., Radiation Protection Rules, Dose limits stipulated by these bodies. Dose limits observed in India.
  - Radiation protection philosophy, Principles of radiation protection, concept of ALI & DAC (with suitable problems). Fundamentals of ICRP respiratory model, entry through ingestion, GI track model.
  - Principles of radiation detection and monitoring: Basic operating principles of a) Gas b) Scintillation (including thermo luminescence detectors) and c) Semiconductors detectors.
  - Type of Radiation monitors/Radioactivity measurement methods adopted for radiation protection.
- Radiation protection and measurement (External and Internal):
  - Control of external exposures (with problems in each case).
  - Buildup concept, shielding from alpha, beta, gamma and neutron sources. Shielding from mixed sources.
  - Routes of intake of radioactive material,
  - Radiotoxicity and classification of laboratories, design of laboratory for radioactive work, Radioactive waste classification and management. Personal monitoring, area-monitoring, air monitoring. Bioassay, whole body counting techniques. Use of personal dosimeters (TLDs, pocket dosimeters)
- Radiation Protection procedures: Procedures followed in radiation work places, work permits, zoning concept, contamination control methods, and rubber areas, spill pack (gloves + absorbing paper), Decontamination techniques. Precautions during radioactive source storage and handling, safety during transportation. Nature of duties and responsibilities of Radiation Safety Officer/Health Physicist.
- Nuclear Accidents, Emergency Preparedness and Management: Reasons for accidents, classifications of accidents, International Nuclear Events Scale. Types of emergency, emergency preparedness.
- Radiological aspects and Environmental Impact of FBRs: Radiological aspects of Fuel Cycle Facilities
- Industrial Safety Aspects: Introduction to Industrial Safety (accident prevention technique, Job safety analysis, control measures), Factories Act, 1948 & Atomic Energy Factories Rules, 1996,ndustrial safety aspects (Physical and Chemical Hazards),Industrial safety aspects (safety in Machineries, hand tools & Material handling equipments, personal protective equipments, etc)Construction safety (includes Electrical Safety & Work Permit System)

Course Outcomes:

Students will understand radiation sources, dosimetric quantities, interaction of alpha, beta, gamma and neutron radiation with matter, and biological radiation effects. They will apply ALARA principles, ICRP models, radiation monitoring techniques (gas, scintillation and semiconductor detectors), shielding methods, radioactive waste management, emergency preparedness, and regulatory safety standards.

References:

1. Introduction to Health Physics – Herman Cember
2. Introduction to Radiation Protection – Alan Martin
3. IAEA Regional Basic Professional Training Course on Radiation Protection (Course jointly organized by BARC and IAEA), October 26-Dember 18, 1998
4. Nuclear Radiation Detection - W.J. Price
5. Radiation Detection and Measurement - G.F. Knoll
6. Biological Effects of Radiation – J.E. Coggle
7. Nuclear Radiation Detectors by S.S. Kapoor and V.S. Ramamurthy (Publication: New Delhi, Wiley Eastern Ltd, 1986)
8. Atoms, Radiation and Radiation Protection by James E. Turner 1986
9. Problems and solutions in Radiation Protection by James E. Turner, 1988
10. Guide Lines for Hazard Evaluation Procedures – American Institute of Chemical Engineers
11. Risk Analysis in the Process Industries: The Institute of Chemical Engineers, England.
12. Loss Prevention in The Process Industries: Hazard Identification, Assessment and Control; Vol-1, 1996 2 Edition, Frank P Lees.

NR: Nuclear Reactors (50 Lecture Hrs)

Coordinators: Shri D.Nagasivayya (dnsiva@igcar.gov.in)

Course Details:

- **Mechanical Aspects of Power Plant Engineering:**

  Basic thermal Cycle used in NPS, means of Improving cycle efficiency, Major components in thermal and Nuclear stations, Heat Balance typical calculations, Details of equipment – Steam Generators, Turbines, Condensers, Feed Water heaters, De-aerator feed pumps, condensate and other pumps: condenser cooling water system: C&I; steam pressure control, steam discharge and steam dumping features.

- **Thermal Power Reactors :**

  Layout of Nuclear Power Plant; Zoning requirements: layout of typical PHWR; description of layout in the reactor building; Special requirements for'; nuclear components regarding material selection, reliable operation with examples of pumps, valves, heat exchangers etc. operating environment (including capabilities to withstand seismic loads). Description of calandria, end shield and coolant channel (including fitting). Description of reactivity control scheme and related hardware e.g. zone control, regulating rods, absorbers, shutdown systems etc. Fuel and Fuel transfer system; Primary Heat Transport System; emergency core cooling system; Moderator system; Auxiliary System; Description of process Water, Fire Water and Ventilation system (emphasis on role played as safety support systems); Containment and associated safety systems to mitigate consequences of accidents and contain reactivity release; ultimate heat sink and heat removal paths.A brief overview of PWR, BWR and AHWR

- **Fast Power Reactors :**
  - Fast Reactor Physics and Safety: Role of FBR’s, breeding ratio, doubling time, core design features - Static and Dynamic, control rod design, shielding principles, Fuel management, safety.
  - Overview of FBR: FBTR and PFBR. Comparison of FBRs: Core & important design parameters, comparison of core components, major primary and secondary system components.
  - Core Engineering: Description, choice of core materials, Engineering design of core, High temperature design methods.
  - Heat Transport Systems: Introduction, Design of IHX, SG, sodium pump, sodium piping, Decay heat removal system.
  - Instrumentation & Control: FBR instrumentation requirements, Neutronic Instrumentation and failed fuel detection methods, Reactor protection instrumentation and process instrumentation.

- **Sodium Technology**
  - Properties of Sodium: Physical and chemical properties, (Hazardous nature and sodium-air, sodium-water reactions), heat transfer properties, Manufacture of sodium, Heat transfer in liquid metals, Hartman effect in liquid metals

- Sodium Systems – General Description: Components of a sodium system, process, cover gas system etc.
- Impurities in Sodium, Purification Methods: Impurities in sodium, purification methods, impurity monitors, (plugging indicator, on-line hydrogen, oxygen and carbon monitors)
- Sodium System: Components, piping and Quality Control Materials, design aspects, tanks, valves, vapor traps and other mechanical engineering aspects, sodium centrifugal pumps, high temperature piping for sodium, fabrication aspects, quality control
- Sodium Pumps and flow meter: Electromagnetic pumps and flow meter for sodium systems
- Electrical Systems for Sodium Loops: Electrical supply, heating systems, heater control, types of power supply

- Instrumentation and Control: Level, leak, flow and temperature monitoring, pressure measurement, control of process parameter in sodium systems, under sodium viewing.
- System Operation Aspects: Sodium system pre-commissioning checks, methods of checking all components, limiting conditions of operation, surveillance checks etc.
- Sodium component cleaning, fire and safety
- Sodium removal and disposal methods, sodium fire and extinguishment methods, system and industrial safety aspects.

Course Outcomes:

Students will understand thermal cycles, steam generators, turbines, condensers, PHWR layout, reactor control systems, emergency core cooling systems, and containment safety features. They will analyze fast breeder reactor design, heat transport systems, sodium technology, neutronic instrumentation, failed fuel detection, and reactor protection systems.

References:

1. Nuclear Power Engineering, M. EI-Wakil, Mcgraw Hill Book Co., New York.
2. Steam Power Station, G.A. Gassort.
3. Power Plant Engineering & Economics, Strosal & Vapet.
4. Central Electricity Generating Board (London), Modern Power Station Practice, Nuclear Power Generation Ed 2, Oxford, Pergamon, 1971.
5. Weisman. J. Modern Power Plant Engineering, Englewood Cliffs, Prentice Hall, 1985.
6. IAEA Directory of Nuclear Reactors, Vol. IV, Power Reactors, Vienna.
7. Fast Reactor Technology: Plant Design, J. G. Yevick, M.I.T. Press.
8. Fast Breeder Reactors, A.E. Waltor & A.B. Reynolds, Permagon Press.
9. Status of liquid metal cooled fast reactor technology, IAEA-TECDOC—1083
10. Material for Sodium Technology portion will be provided during the course

RE: Reactor Engineering (40 Lecture Hrs)

Coordinators: Shri Sriramachandra Aithal
(saithal@igcar.gov.in)

Course Details:

- **Core design**
  - Introduction - Role of FBR, Main Characteristics of LMFBR, Sodium as coolant, Core Configuration, Definition of NSSS & BOP, Pool & Loop Type Design.
  - Fixing Size & Parameters of LMFBR - Test Reactor, Commercial & Prototype Reactor, Unit energy cost, Hot Spot temperature of Clad, Optimisation on Pin Diameter.
  - Definition of Smear Density, DPA & Burn up.
  - Fast Reactor Core – Fuel, Basic Requirements, Choice of fuel material, Candidates for Fuel, Swelling, Fabrication cost, Reprocessing, Negative Doppler coefficient, Thermal expansion, Burnup.
  - Absorber – required features, candidate materials
  - Structural Material in Core - Requirements of Core Structural Material, Effect of Neutron Irradiation on SS, Radiation Hardening, Embrittlement, Void Swelling, Irradiation Creep, Effect of Swelling & irradiation induced creep, Efforts to reduce swelling.
  - Sub-Assembly (SA) Design - Basis for Number of pins in a fuel SA, Pin spacers, Gas Plenum, Duct considerations, Volume Fraction, Assembly Length.
  - Other Subassembly design - Blanket, CSR, DSR, Reflector, Inner B4C, Outer B4C and Steel Shielding subassemblies.
  - Thermal Design of Fuel Pin - Thermal Analysis, Causes for fuel restructuring, Developing Analytical Model, Necessary physical parameters, Na Heat Transfer coefficient, Hot spot Analysis, Calculation of temperature distribution across fuel pin.
  - Mechanical Design of Fuel Pin - Failure Criteria for Pin, Strain Limit Approach, Cumulative Damage Fraction, Stress analysis, Cladding wastage.
  - Hydraulic Design of Core - Factors to be reviewed for Core Hydraulic Design - Hydraulic lifting force, Mixing studies, Power flattening & flow zoning, Vibration.
  - Handling of core subassemblies - Inherent problems associated with on-line fuel handling, Fresh SA Handling, Spent SA Handling.

- **Coolant circuits**
  - Selection of coolant for FBRs, thermal, transport, nuclear, chemical and other considerations. comparison between various coolants. Special characteristics of sodium. Its impact on heat transfer and structural mechanics considerations. Selection of structural materials, basis and important alloying elements.
  - Main heat transport system: primary and secondary sodium system, necessity of intermediate loop. Safety Grade decay Heat removal system, Decay heat, necessity for independent system.
  - Features of major components such as intermediate heat exchangers, steam generators, sodium to air exchangers, sodium pumps, electro magnetic pumps, sodium tanks, support design for sodium components from thermo mechanical and seismic considerations, sodium valves and types.
  - Design criteria, Loadings to be considered, Analysis method and validation methodology.
  - Special characteristic of sodium piping, sodium leak, sodium fire, various types of leak detectors, continuous and discontinuous level detectors etc.
  - Sodium purification loop, oxygen control, plugging indicator, cold trap, characteristics and features.
  - Operating experiences of fast reactors, failures and sodium leaks reported for Phenix,

Monju, PFR and other fast reactors, reasons for leak and remedy.

Course Outcomes:

Students will develop expertise in LMFBR core design, fuel selection, smear density, burnup, DPA, absorber materials, and structural material irradiation effects. They will analyze fuel pin thermal-mechanical design, hydraulic core design, sodium coolant circuits, intermediate heat exchangers, steam generators, decay heat removal systems, sodium purification, and reactor component safety considerations.

References:

1. Fast Breeder Reactors - Walter, A.E. & Reynolds, A.B., PERGAMON Press.
2. Fast Reactor Technology - Plant Design - Yevick, J.G., M.I.T. Press.
3. Fundamental Aspects of Nuclear Reactor Fuel Elements - Donald R. Olander, U.S.Department of Energy, 1985.

CORE COURSES

CE1: Nuclear Chemical Engineering (35 Lecture Hrs)

Coordinators: Dr. K. A. Venkatesan
(kavenkat@igcar.gov.in)

Course Details:

- An Introduction to Nuclear Chemical Engineering General Introduction and course schematics.
- Production of Nuclear Materials Production of nuclear fuels (i.e.)uranium, thorium and zirconium form ores. Alternate sources for uranium Isotope separation technologies for uranium and water Fuel fabrication technologies for various types of reactors Less common nuclear materials like Zr, Hf, Th, Be,V, Nb and Ta.
- Solvent Extraction of Nuclear Materials Introduction to archival extractants and flowsheets Science and technology of primary extractant (TBP) Alternate extractants for fuel reprocessing applications Extractants for nuclear waste management applications Classical and novel nuclear solvent extraction equipment Criticality and its prevention. Other safety aspects.
- Nuclear Fuel Reprocessing PUREX, Advanced PUREX, SuperPUREX processes Reprocessing of thermal reactor (PHWR and AHWR) Fuels Reprocessing of fast reactor (FBTR & PFBR) Fuels UREX process and its variants Supercritical Fluid Extraction based Superdirex Process Pyrochemical and other non-aqueous processes for reprocessing.
- Nuclear Waste Management Characterization of nuclear wastes Conditioning and remediation. Post-PUREX and Post-UREX processes for isolation of important radionuclides (TRUEX, UNEX, ARTIST, SETFICS, SESAME etc.) Decontamination and decommissioning.
- Modeling and Simulation in Nuclear Chemical Engineering Generation of SX data by conventional & AKUFVE techniques Modeling of solvent extraction data Computer codes for simulation of nuclear SX Simulation of solvent extraction process flowsheets Experimental design based variation analysis of flowsheets.

Course Outcomes:

Students will understand production of nuclear fuels (U, Th, Zr), isotope separation technologies, fuel fabrication, and solvent extraction science using TBP and alternate extractants. They will be able to analyze PUREX, Advanced PUREX, UREX, pyrochemical reprocessing processes, nuclear waste management strategies, criticality safety, and modeling & simulation of solvent extraction flowsheets.

References:

1. Benedict M., Pigford T.H. and Lewi H. Nuclear Chemical Engineering, McGraw Hill. 2nd ed. (1981).
2. Long, J.T. , Engineering for Nuclear Fuel Reprocessing, American Nuclear Society, IL (1978).
3. Schulz. W.W, Navratil, J.D. and Talbot A.E., Science and Technology of Tributyl Phosphate, Vol.1, CRC Press Inc., Boca Raton, FL (1984).
4. Schulz. W.W, Burger, L.L.,Navratil, J.D. and Bender K.P., Science and Technology of Tributyl Phosphate, Vol.3, CRC Press Inc., Boca Raton, FL (1984).
5. Knief, R.A. Nuclear Energy Technology, Hemisphere Publishing corporation, NY, (1981)
6. Vilani, J., Isotope Separation, (IGCAR library) 7. Selected IGCAR Reports Concurrent literature on AFCI, UREX and allied processes.

CE2: Chemical Engineering Thermodynamics (40 Lecture Hrs)

Coordinators: Dr. Vidya Sundararajan
(vidya@igcar.gov.in)

Course Details:

- Classical thermodynamics - the scope of classical thermodynamics, basic concepts and definitions. Laws of thermodynamics and its applications.
- Thermodynamic Properties of pure substances and mixtures.
- Multicomponent systems: the chemical potential, fugacity, activities, and activity coefficients.
- Solubilities of gases in liquids, solids in gases and in liquids.
- Vapour liquid equilibria at low and high pressure. (Van Laar, Peng-Robinson equations). Thermodynamics of super critical fluid.
- Liquid-Liquid equilibria.
- Models for Non ideal, Non-electrolyte solutions and ionic liquids.
- Solution thermodynamics.
- Phase Equilibrium: Phase rule, phase diagrams, the differential approach for phase equilibrium relationships, pressure-temperature relations, Equilibrium in systems with supercritical components, phase stability applications.
- Chemical Reaction Equilibria: Equilibrium constants for Homogeneous and heterogeneous reactions.
- Statistical Thermodynamics.

Course Outcomes:

Students will apply the laws of thermodynamics, thermodynamic properties of pure substances and mixtures, fugacity, activity coefficients, and chemical potential to engineering systems. They will analyze phase equilibria (VLE, LLE), supercritical fluids, reaction equilibria, solution thermodynamics, and statistical thermodynamics for real and non-ideal systems.

References:

1. Denbigh, K. G., The Principles of Chemical Equilibrium, Cambridge, 1971.
2. Tester, J. W. and Modell, M., Thermodynamics and its Applications, 3rd ed., Prentice-Hall, 1997.
3. Bejan, A., Advanced Engineering Thermodynamics, Wiley, 1988.

CE3: Transport Phenomena (40 Lecture Hrs)

Coordinators: Shri Sourabh Agarwal
(sourabh@igcar.gov.in)

Course Details:

- Phenomenological description of continuum approach. Reynolds transport theorem. Basic laws of conservation of mass, momentum and Energy and Multicomponent systems

- Transport properties. Modeling of Engg systems and the specification of boundary conditions. Shell balances, Navier-Stokes equations; Momentum, Heat and Mass transfer in steady and unsteady viscous flows; turbulent flows; shell and differential thermal energy balances; steady and unsteady conduction; laminar, forced and natural convection; shell and energy balances of mass of species; diffusion under various driving forces, diffusion with chemical reaction; convective diffusion in dilute solutions; integral balances. Transport coefficient and the macroscopic treatment of momentum, Energy and mass transport in complex system.

Course Outcomes:

Students will formulate and solve mass, momentum, and energy conservation equations using continuum approach, Reynolds transport theorem, and Navier–Stokes equations. They will analyze laminar and turbulent flows, heat and mass transfer, diffusion with chemical reaction, convective diffusion, and transport coefficients in complex engineering systems.

References:

1. Bird, R.B, Stewart, W.E. and Lightfoot, E.N., Transport Phenomena, Wiley, 1994.
2. Denn, M.M, Process Fluid Mechanics, Prentice Hall, 1980.
3. Whitaker, S., Fundamental Principles of Heat Transfer, NewYork, Pergamon, 1997.
4. Cussler, E, L., Diffusion: Mass Transfer in Fluid Systems, Cambridge, 1985.
5. Welty, J.R., C.E. Wicks and R.E. Wilson - " Fundamental of momentum, heat and mass transfer ", John Wiley and Sons, 1976.
6. Sissom, L.E. and D.R.Pitts - " Elements of Transport Phenomena ", McGraw Hill, New York, 1972.
7. Brodkey, R.S. and H.C.Hershey - " Transport Phenomena ", A United Approach McGraw Hill, 1988.

CE4: Multi-phase Flow Systems (40 Lecture Hrs)

Coordinators: Dr. K. A. Venkatesan
(kavenkat@igcar.gov.in)

Course Details:

- Multiphase flows and Classification of Multiphase, Flow Patterns (gas-liquid, liquid-liquid and gas-solid and gas-liquid-solid) - flow pattern and flow regime map with and without phase change. One-dimensional models for continuity, momentum and energy transfer for different models: Multi-dimensional and flow regime specific models.

- Applications of two-phase flow in the design of steam generators, thermo-syphon evaporators, condensers with non condensibles and air lift pumps.

- Hydrodynamic of liquid-liquid flow design variables such as holdup, characteristic velocity and pressure drop.

- Hydrodynamics of solid-liquid flow, homogenous and heterogeneous flow. Design equations for hydraulic transportation. (Liquid-solid mixture transport in pipe: flow pattern, accelerating length, velocity profile and pressure drop for turbulent slurry flow.).

- The phenomena of fluidization and its industrial application. Characteristics of particles. Principle of fluidization and mapping of various regimes. Two phase theory of fluidization. Bubbles in fluidized bed. Entrainment and Elutriation. Fast fluidized bed. Mixing, segregation and gas dispersion. Heat and mass transfer in fluidized bed. Solid-liquid fluidized bed and three phase fluidized bed. Design of fluidized bed reactors.

Course Outcomes:

Students will understand classification of multiphase flows, flow regimes, and one-dimensional continuity, momentum, and energy models for gas–liquid, liquid–liquid, and solid–liquid systems. They will apply two-phase flow concepts, slurry transport, fluidization theory, pressure drop correlations, and fluidized bed reactor design to industrial applications.

References:

1. Wallis, G.B. - " One Dimensional Two phase flow", McGraw Hill Book Co., New York, 1969.
2. Govier, G.W. and K.Aziz., - " The flow of Complex Mixtures in Pipes ", Van Nostrand Reinhold Co., New York, 1972.
3. Brodkey, R.S. - " The Phenomena of Fluid Motions ", Addison - Wesley Publishing Co., New York, 1967.
4. Gad Hestsroni, (Ed.in Chief) - " Handbook of Multi Phase Systems ", Hemisphere Publishing Corporation, Washington and McGraw-Hill Book Company London, 1982.
5. Two-phase flow in pipe lines and heat exchangers – D.Chisholm, Longman Inc, NewYork.
6. Fluidization Engineering- Author: Daizo Kunni and Octave Levenspiel, ButterworthHeinemann
7. Fluidized bed technology in Materials Processing, -Author: C. K. Gupta and D. Sathiyamoorthy, CRC Press.
8. Chemical Reaction Engineering, - Octave Levenspiel,Wiley Eastern Limited.
9. Handbook of separation techniques for Chemical Engineers, - Philip A. Schweitzer,: McGrawHill.

CE5: Code Design for Pressure Vessels & Piping (25 Lecture Hrs)

Coordinators: Shri S. D. Sajish
(sajish@igcar.gov.in)

Course Details:

- Membrane theory for thin shells, stresses in cylindrical, spherical and conical shells, dilation of above shells, general theory of membrane stresses in vessel under internal pressure and its application to ellipsoidal and torispherical end closures.

- Thick cylinder and sphere and derivation of Lame's equations. Derivation of ASME Sec. VIII Div. 1 & Div -2 equations for cylindrical spherical and conical shells, ellipsoidal and torispherical end closures.

- Bending of circular plates and determination of stresses in simply supported and clamped circular plate. Basis of ASME equation for flat closures.

- Openings, nozzles and external loading. Stress concentration in plate having circular hole due to bi-axial loading. Theory of reinforced opening and reinforcement limits.

- Beam on elastic foundation and its application to thin-walled pressure vessels. Extent and significance of load deformation on pressure vessel. Reinforcement rules for ASME, Sec. VIII Div.1. Local Stresses in shells due to external loadings from nozzles and lugs etc.

- Bolted Flanged joints. Types of flange joints. Types of gasket and their selection. Bolting design. Flange loads and moments. Design of flange as per ASME Boiler and Pressure Vessel and B 31.3 Code.

- Supports for vertical and horizontal vessels. Design of base plate and support lugs. Types of anchor bolt, its material and allowable stresses. Design of saddle supports.

- Buckling of vessels under external pressure. Elastic buckling of long cylinders, buckling modes, Buckling (collapse) coefficients. ASME procedure for design of vessels under external pressure. Design for stiffening rings. Design of shells for axial compression.

- Derivation of TEMA Design equation for tube sheets. Background of the ASME design rules for tube sheets.

- Piping thickness as per ANSI ASME B31.1 and B31.3 piping code. Flexibility factor and stress intensification factor. Design of piping system as per B31.1 piping code. Design of piping for hazardous fluid as per B31.3

- Design consideration for pressure vessel. Design pressure and temperature, Allowable stresses, Impact toughness requirement as per ASME Sec. VIII Div.1 code. Non-destructive examination of welds as per ASME Sec.VIII, Div.1 code. Difference between Sec. VIII Div.1 & Div.2.

Course Outcomes:

Students will be able to design pressure vessels and piping systems using membrane theory, Lame’s equations, buckling analysis, and reinforced opening theory. They will apply ASME Section VIII Div.1 & Div.2, B31.1 and B31.3 codes for flange design, supports, nozzles, piping flexibility, and safety compliance.

References:

1. Harvey J F , 'Pressure vessel design' CBS publication.
2. Brownell. L. E & Young. E. D , 'Process equipment design', Wiley Eastern Ltd., India.
3. ASME Pressure Vessel and Boiler code, Section VIII Div 1 & 2, 2003.
4. American standard code for pressure piping , B 31.1.
5. Standards of Tubular Exchanger Manufacturers Association, Eighth Edition ,1998.

CE6 & CE10: Computational Fluid Dynamics & Heat Transfer (40 Lecture Hrs)

Coordinators: Shri Rajendra Kumar(mkr@igcar.gov.in),
Dr. K.A.Venkatesan(kavenkat@igcar.gov.in)

Course Details:

- **Basics of Fluid Flow, Heat Transfer and Numerical Analysis:**
    - Kinematics of fluid flow. Streamline, streakline and pathline; streamfunction, vorticity and deformation of a fluid element.
    - Basic equations governing heat conduction, fluid flow and mass transfer (viz. the continuity', momentum and energy' equations) with special reference to Navier-Stokes and Bemoulli equations.
    - Classification of Partial Differential Equations (PDEs).
    - Discretization of conduction equation with Dirichlet, Neumann and periodic boundary conditions, by ADI and TDMA methods.
    - Temporal integration: explicit, implicit scheme.
    - Discretization of convection, upwinding, Streamline-Upwind Petrev Galerkin method.
    - Discretization of convection-diffusion problem: exponential scheme, power-law scheme

- **Numerical Solution of Complete Fluid Flow and Energy Equation:**
    - Formulations of governing equations used in numerical simulation:
    - Stream function-temperature formulation.
    - Stream function-vorticity-temperature formulation.
    - Velocity-vorticity-temperature formulation: Poission, Cauchy-Riemaim and Biot-Savart form.
    - Primitive-Variable (P-V-T) formulation.
    - Pressure velocity coupling for incompressible flow.
    - Staggered, Non-Staggered Grid (momentum interpolation, pressure-weighted interpolation).
    - Discussion on MAC, PISO, SIMPLE and SIMPLEN family of Methods.
    - Simple grid generation techniques for structured grid:
    - Elliptic. parabolic and hyperbolic equation method.
    - Grid adaptation.
    - Domain decompositions in CFD and heat transfer.
    - SIP and preconditioned conjugate gradient methods for solution.
    - Numerical Solution of Reduced Boundary Layer Equations: BVP, Keller box method for laminar and forced convective boundary layer problems.
    - Numerical solution of approximate equations for natural convective heat transfer problems including porous medium.
    - Mathematical formulation and numerical solution of compressible flows and heat transfer.

- **Laminar Boundary Layer and Forced Convective Heat:**

- Formulation of differential equation for hydrodynamic and thermal boundary layer.
- Different analytical method of reduction of boundary layer equations and theoretical formulation of boundary layer thickness.
- Study of jets and inlet flow and flow separation in the light of Boundary Layer Theory.
- Convective heat transfer for internal and external flows.
- Low and high Prandtl number limits and different thermal boundary conditions Numerical Solution of

Reduced Boundary Layer Equations: BVP, Keller box method

- **Turbulent Flow and Heat Transfer:**

- Reynolds decomposition for turbulence
- Prandtl's mixing length theory, Mixing length models
- Structure of turbulent boundary layer over flat plate and through circular cylinder
- Calculation of friction factor and drag coefficient
- Analytical and semi-analytical correlations for calculating heat transfer coefficients
- Analogy between heat and momentum transfer
- Reynolds analogy, von Karman-Prandtl analogy, Martenelli analogy, Lyons analogy
- Turbulence Modeling:
- Eddy diffusivity models: k-ε and k-ω) models, RNG based k- ε model
- Reynolds stress models: algebraic and differential models
- Low Reynolds number models
- Large eddy simulation: Smagorinsky and Dynamic sub-grid scale models.

- **Natural Convection:**

- Basic Equations of natural convection
- Boussinesq approximation
- Derivation of Dimensionless groups from basic equations
- Analytical approximations
- Numerical solution of approximate equations.

- **Reactor Heat Transfer:**

- Pressure drop in rod cluster fuel element friction, local acceleration and elevation pressure drop in wire-wrap & grid spacers; effect of creep and bundle misalignment on PHWR bundle pressure drop. Flow orificing objectives & methods; effect of orificing in BWR.
- Hot spot factors: Classification, basic statistical relationship, determination of subfactors, multiplicative & statistical methods of combining subfactors. Subchannel analysis of rod cluster mixing mechanisms, mixing parameters, introduction to computer codes.
- low loops: Determination of operating point during forced and natural circulation; Loss of flow accident; Decay heat generation and flow coast down in primary loop. Transition to thermosyphon cooling; steady state theory of thermosyphon loops. Transient and stability behaviour of the thermosyphon loops. Loss of coolant Accident; Events during blow down, description of emergency core cooling system; flooding and sputtering.
- Radiation heat transfer: Introduction; Reflection, absorption, transmission and emission; concept of black and grey body; total emissive power and Stefan-Boltzmann constant. Kirchoff's law. Radiation heat transfer between two bodies: shape factor & law of reciprocity; radiation heat transfer between two grey bodies.

- **Heat Transfer With Phase Change**

  - Introduction of two phase flow and basic relations; flow regimes in adiabatic and diabatic vertical co-current flow and in adiabatic co-current horizontal flows.
  - Basic equa`tions of two phase flow; Homogenous & separated flow models for two hase flow; void fraction & phase velocity ratio (Zivi's model)

- Introduction to boiling heat transfer and bubble nucleation; Regimes in boiling heat transfer (a) pool boiling (b) flow boiling: Heat transfer correlation for pool boiling (Rohsenow's correlation) and flow boiling (Chen's correlation)
- Condensation heat transfer: Nusselt's theory and its limitations: Jet condensation fundamentals and its application in containment cooling.
- Critical heat flux: Various models of critical heat flux, CHFR, MCHFR. Critical power concept.
  Post dryout heat transfer: Various models available for calculation of heat transfer coefficient.
  Critical Flow: Models for single – phase and two-phase critical flow.

Course Outcomes:

Students will formulate and numerically solve Navier–Stokes, energy, and convection–diffusion equations using finite volume/finite difference methods, TDMA, SIMPLE, PISO, and grid generation techniques. They will analyze laminar and turbulent flows, boundary layers, natural and forced convection, boiling, condensation, reactor heat transfer, CHF, LOCA, and radiation heat transfer.

References:

1. Knudsen, J.G. and Katz, D.L. (1958): Fluid Dynamics and Heal Transfer, McGraw-Hill: NY.
2. Bird. R.B., Stewart, W.E. and Lightfoot, E.N. (1960): Transport Phenomena, John Wiley & Sons: NY.
3. Schhchting, S. (1979): Boundary' Layer Theory, 7* ed., McGraw-Hill : NY.
4. Tennekes, H. and Lumley, J.L. (1972): A First Course in Turbulence, MIT Press: Cambridge.
5. Piquet, J. (1999): Turbulent Flows: Models and Physics, Springer-Verlag: Berlin.
6. Holman, J.P. (1997): Heat Transfer, 8"" ed., McGraw-Hill : NY.
7. Kays, W.M. and Crawford, M.E. (1993); Convective Heat Transfer, McGraw-Hill: NY.
8. Gebhart, B., et al. (1988): Buoyancy-Induced Flows and Transport, Hemisphere.
9. Barret, K. (1982): Numerical Modelling in Diffusion-Convection, Pentach Press : London, Polymouth.
10. Hussaini, M.Y. et al. (1997): Up-wind and High Resolution Schemes, Springer-Verlag : Berlin.
11. Warsi, Z.U.A. (1998): Fluid Dynamics: Theoretical and Computational Approaches, 2"" Ed., CRC Press.
12. Cebeci, T. and Bradshaw, P. (1984): Physical and Computational'Aspects of Heat Transfer, Springer-Verlag.
13. Quartepelle, L. (1993): Numerical Solution of the Incompressible Navier-Stokes Equations, Birkhauser Verlag.
14. Patankar, S.V. (1982): Numerical Heat Transfer and Fluid Flow, Hemisphere.
15. Versteeg, H.K. and Malalasekera, (1996): An Introduction to Computational Fluid Dynamics: the Finite.
16. Volume Method, Addison-Weslev.
17. Gresho, P.M. et al.. (1999): Incompressible Flow and the Finite Element Method, John Wiley & Sons.
18. Comini, G., et al. (1994): Finite Element Analysis of Heat Transfer, Taylor & Francis : Washington DC.
19. Canuto, C., et al. (1988): Spectral Methods in Fluid dynamics, Springer-Verlag :NY, 557pp.
20. Thompson, J.F., Soni, B. and Weatherill, N.P. (1998): Handbook of Grid Generation, CRC Press.
21. Glowinski. R., et al. (Eds.) (1997): Domain Decomposition Methods in Science and Engineering, Wiley.
22. Turek, S. (1999): Efficient Solvers for Incompressible Flow Problems, Springer-Verlag.
23. Wesseling, P. (1992): An Introduction lo Multigrid Methods. Wiley : NY.
24. Wagner, S. (1995): CFD on Parallel Systems, Friedrich Wieweg & Sons.

CE7: Advanced Chemical Reaction Engineering (25 Lecture Hrs)

Coordinators: Shri J. Kodandaraman
(jkr@igcar.ac.in)

Course Details:

- Stoichiometry rates and thermodynamics of chemical reactions. Influence of concentration and temperature. Reaction mechanism. Generalized balance equation for reactive systems.
- Collection and analysis of rate data: differential method, Integral method, Graphical method, polynomial fit method, Methods of initial rates, Methods of excess, Methods of half life. Kinetics of homogeneous and heterogeneous reactions.
- Conservation equations for chemically reacting mixtures; heterogeneous catalytic reactions.
- Chemical reactions and processes of transport: external diffusion effects on heterogeneous reactions, diffusion and reaction in porous catalysts.
- Design and analysis of chemical reactors: Isothermal and non-isothermal reacting systems, catalytic and non-catalytic reactions systems.
- Uniqueness and multiplicity of steady states, stability analysis. Non-ideal reactors: distributions of residence time for chemical reactors, models for nonideal reactors.
- Modeling of multiphase reactors: fixed, fluidized, trickle bed, slurry etc.

Course Outcomes:

Students will analyze reaction kinetics, stoichiometry, reaction mechanisms, and rate data using differential, integral, and initial rate methods. They will design isothermal and non-isothermal reactors, catalytic and multiphase reactors, and study steady-state multiplicity, stability, non-ideal reactor behavior, and residence time distributions.

References:

1. Aris R., Elementary Chemical Reactor Analysis, Prentice-Hall 1969.
2. Foggler, H. S., Elements of Chemical Reaction Engineering, Prentice Hall of India, 1994.
3. Froment G.F. and Bischoff K.B., Chemical Reactor Analysis and Design, John Wiley, 1994.
4. Smith J.M. - " Chemical Engineering Kinetics ", McGraw-Hill, 1981.

CE-EL3: Artificial Intelligence Methods & Applications (30 Lecture Hrs)

Coordinators: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- **Robotics**
  - Forward and Inverse kinematics, Jacobians,
  - Manipulator Dynamics, Trajectory generation,
  - Sensors, Manipulator Control, Force control,
  - Path planning, Mapping &Localisation of Mobile robots,
  - Behavior based control, Robot learning.
- **Genetic Algorithm**
  - Introduction to GA and its terminology,
  - GA operators and working principle of GAs.
  - Different selection mechanisms, selection pressure vs. population diversity,
  - premature convergence, fitness scaling and elitism.
  - Constraint handling. Multimodal function optimization.
  - Application of GAs, real-coded GAs.
  - Multiobjective optimization, difference with single objective optimization, concept.
  - of Dominance and Pareto-optimality. Multiobjective GAs. 3. Fuzzy Logic.
  - Introduction;Need, Historical Development and Perspective of applications.
  - Crisp and Fuzzy Sets, Operations on fuzzy Sets.
  - Fuzzy Arithmetic, Fuzzy relations, Fuzzy logic.
  - Possibility Theory and Uncertainty Based information.
  - Construction of Fuzzy Sets (with examples), Approximate Reasoning.
  - Applications; Pattern Recognition and Process Control (with examples).

Course Outcomes:

Students will apply robotics concepts including kinematics, dynamics, trajectory planning, sensing, and robot learning. They will implement genetic algorithms, fuzzy logic, multi-objective optimization, Pareto optimality, and uncertainty modeling for applications in process control, pattern recognition, and intelligent systems.

References:

Material will be provided during the course.

CE8: Process Analysis and Control (25 Lecture Hrs)

Coordinators: Dr. K. A. Venkatesan
(kavenkat@igcar.gov.in

Course Details:

- Distinctive characteristics of dynamics of chemical process systems; process control objectives and strategies; material balance and product quality control Review of dynamic behavior of linear systems and their control system design. Linear processes with difficult dynamics.

- Nonlinear process dynamics; phase-plane analysis; multiple steady-state and bifurcation behavior; Process Identification; Controller design via frequency response analysis; Model based control; Cascade, feed forward & ratio control; Controller design for nonlinear systems; Introduction to multivariable systems. Interaction analysis and multiple single loop design.

- Design of multivariable controllers; Introduction to sampled-data systems; Tools of discrete time systems analysis; Dynamic analysis of discrete-time systems; Design of digital controllers; Introduction to model predictive control; Convolution models; Model predictive control of MIMO systems

Course Outcomes:

Students will model dynamic behavior of linear and nonlinear chemical processes using material balances, transfer functions, and phase-plane analysis. They will design PID, cascade, feedforward, multivariable, digital, and model predictive controllers, and analyze MIMO systems, interaction effects, and process identification techniques.

References:

1. Buckley P.S., Techniques of Process Control, John Wiley, 1964.
2. Douglas, J.M., Process Dynamics and Control, Vols, I & II, Prentice Hall, 1972.
3. Stephanopoulos G., Chemical Process Control, Prentice Hall, 1988 Current Literature.
4. Emanule, S.Savas - " Computer Control of Industrial Processes ", McGraw-Hill London, 1965.
5. Peter Harrior - " Process Control ", Tata McGraw Hill publishing Co., Ltd., New Delhi., 1977.

CE9: Advanced Mass Transfer (40 Lecture Hrs)

Coordinators: Dr. K. A. Venkatesan
(kavenkat@igcar.gov.in)

Course Details:

- Theories of mass transfer with and without chemical reaction-with examples from gasliquid, liquid-liquid, and liquid-solid systems; Rate based approaches for design. Film, Penetration & Surface Renewal models, Solvent extraction theory.
- Selection and design of contacting equipment in nuclear chemical industries-Spray, packed and tray columns trickle bed reactors. Extraction equipment: mixer settlers, centrifugal contactors, pulsed extractors, hollow fibre extractors. Adsorption and ion exchange equipment.
- Membrane separation and other advanced mass transfer processes. Process intensification approaches. (few hours for seminar by TSO's).

Course Outcomes:

Students will understand mass transfer theories including film, penetration, surface renewal models, and solvent extraction with chemical reaction. They will design contacting equipment such as packed columns, mixer settlers, centrifugal contactors, adsorption, ion exchange, and membrane separation systems, with emphasis on nuclear chemical process applications.

References:

1. Transport phenomena in liquid extraction – G.S. Laddha and T.E. Degaleesan. McGraw Hill, 1978.
2. Separation process principles – J.d. Seader, Ernest J.Henley. John Wiley & Sons. 2nd Ed. 2005.
3. Mass transfer – Thomas K.Sher wood, Robert L.Pigford, Charles R. Wilkey. McGraw hill.
4. Mass transfer operations - Robert E. Treybal. Mcgraw-hill (1980).
5. Handbook of solvent extraction – The. C. Lo. Malcolm, H.I. Baird, Carl Hanson (editor), Krieger Pub. Co. Reprint edition (Feb 1991)

DETAILED COURSE STRUCTURE

Foundation Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	EM	Engineering Mathematics	35	2
2.	MM	Materials and Metallurgy	25	1
3.	RP	Fast Reactor Physics and Shielding	35	2
4.	HP	Health Physics and Radiological Safety	25(15 T+10 L)	1
5.	NR	Nuclear Reactors	50	3
6.	RE	Reactor Engineering	40	2
		FOUNDATION TOTAL	**210**	**11**

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	EL2	Reactor Control Engineering	20	1
2.	EL3	Nuclear Instrumentation	20	1
3.	EL4	Reliability Engineering	20	1
4.	EL5	Software Engineering	20	1
5.	EL8	Human Machine Interface for Reactor Control Instrumentation	45	3
6.	EL10	Modern Control of Dynamic Systems	30	2
		CORE TOTAL	**155**	**9**

Electives (any four)					
Sr. No	**Course Code**	**Subject Title**	**Hours**		**Credits**
			(T)	**(L)**	
1.	EL6	Artificial Intelligence and Digital Signal Processing	40	-	2
2	EL9	Embedded and Computer Based Systems Design	45	-	3
3	EL7	Process Instrumentation	35	-	2
4	EL11	Analytical Instrumentation	25		1
		ELECTIVESTOTAL	**145**	**-**	**8**

FOUNDATION COURSES COORDINATOR

Course	Coordinators	Contact
EM: Engineering Mathematics	Dr. K. Natesan	22109/22856,natesan@igcar.gov.in
	Dr. V. Satish Kumar	26919/26977,vsatish@igcar.gov.in
MM: Materials and Metallurgy	Dr. Vani Shankar	21147/22805,vani@igcar.gov.in
RP: Fast Reactor Physics and Shielding	Shri Rajeev Ranjan Prasad	22737,rajeevphy@igcar.gov.in
HP: Health Physics and Radiological Safety	Dr. S. Chandrasekaran	23556.schand@igcar.gov.in
NR: Nuclear Reactors	Shri D.Nagasivayya	21232,dnsiva@igcar.gov.in
RE: Reactor Engineering	Shri Sriramachandra Aithal	22468/22605,saithal@igcar.gov.in

CORE COURSES COORDINATOR

Course	Coordinators	Contact
EL2: Reactor Control Engineering	Dr. V.L. Anuraj	21537/22907,anuraj@igcar.gov.in
EL3: Nuclear Instrumentation	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
EL4: Reliability Engineering	Dr. M. Ramakrishnan	22611/22254,mramki@igcar.gov.in
EL5: Software Engineering	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
EL8: Human Machine Interface for Reactor Control Instrumentation	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
EL10: Modern Control of Dynamic Systems	Shri Kalyana Rao Kuchipudi	26187, kalyan@igcar.gov.in

ELECTIVES COURSES COORDINATOR

Course	Coordinators	Contact
EL6: Artificial Intelligence and Digital Signal Processing	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
EL9: Embedded and Computer Based Systems Design	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
EL7: Process Instrumentation	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
EL11: Analytical Instrumentation	Dr. K. Sundararajan	24152, sundar@igcar.gov.in

FOUNDATION COURSES

EM: Engineering Mathematics (35 Lecture Hrs)

Coordinators: Dr. K Natesan(natesan@igcar.gov.in),
Dr. V. Satish Kumar(vsatish@igcar.gov.in)

Course Details:

- Computer arithmetic and errors . Types of errors, error estimates and its propagation, Data analysis : Difference tables, Interpolation methods of Lagrange and Hermite, Chebyshev polynomials and Pade's approximation with rational functions. Numerical differentiation of interpolating polynomials. Numerical Integration : Trapezoidal, Monte-Carlo and Gaussian Quadrature methods Solution of algebric and transcendental equations, Newton-Raphson method, Graffe's root squaring method; Data approximation by method of least square, curve fitting.
- Linear vector space and subspaces, Basis, Gram-Schmidt orthogonalization, Linear system of equations: LU decomposition, Cholesky factorization and Gauss-Jordan technique. Iterative techniques using the methods of Jacobi, Gauss-Seidel and over relaxation. Convergence criteria and error estimation. Matrix inverse, Ill conditioned and sparse matrices. Bilinear forms, Principal axes transformation and eigen values, Determination of eigen values and eigen vectors. LU and QR algorithms, Singular matrices and singular value decomposition.
- Ordinary differential equations, Different types of differential equations, Lipschitz theorem and conditions for existence and uniqueness of solutions, Numerical methods for solving differential equations. Method of Euler, Adams and Runge Kutta, Predictor corrector method, Solving stiff equations.
- Probability and Statistics:Probability and Random variables, Binomial, Poisson and Normal distributions, Moments of a distribution, Counting experiments Estimation of model parameters, Confidence intervals, Testing of hypotheses, Goodness of fit, Chi-square test.
- Integral Transforms: Laplace transform, Linearity of LT, LT of derivatives and integrals, Solution of differential equations using LT, Response of electric circuits, Response of damped oscillator to a square wave, Differentiation and integration of LT.Periodic functions, Fourier series representation of functions, Even and odd functions, Determination of coefficients, Fourier integrals. Data compression, Hauffman coding and wavelet transforms.
- Partial Differential Equations, Finite difference method in one and two dimensions, Solution of steady and transient heat conduction and diffusion equations.
- Finite element method, Energy Theorem and integral equations, Weighted residual approximations, Point and subdomain collocation. Galerkin method, Variational principles and Lagrange multipliers. B-splines,Bezier curves, Response surface method, different levels of factorial design.

Course Outcomes:

Students will be able to apply computer arithmetic, error analysis, interpolation methods (Lagrange and Hermite), Chebyshev polynomials, and numerical integration techniques to engineering problems. They will analyze linear vector spaces, LU/QR decomposition, eigenvalue problems, differential equations, probability distributions, Laplace/Fourier transforms, PDEs, and finite element methods for mathematical modeling and computation.

References:

1. Davis, H. T. and Thompson, K., Linear Algebra and Linear Operators in Engineering: with Applications in Mathematica, Academic Press, 2000.
2. Chapra, S.C. and Canale, R.P., Numerical Methods for Engineers, McGraw-Hill, 1985.
3. R. L. Burden and J. D. Faires, Numerical Analysis, 6th ed., PWS-Kent Publishing, 1997.
4. Krishnamurthy, E. V., Computer based numerical algorithms, East West Press, 1976.
5. Gupta, S.K., Numerical methods for Engineers, Wiley (1995).
6. Press, W.H.; Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., Numerical Recipes in Fortran (or C), Cambridge University Press (1992).
7. Scarborough, J. B. Numerical Mathematical Analysis, Oxford and IBH Publishers, 1968.

MM: Materials and Metallurgy (25 Lecture Hrs)

Coordinators: Dr. Vani Shankar
(vani@igcar.gov.in)

Course Details:

- Classification of Materials: Structure, Ferrous and non-Ferrous metals, Polymers, Ceramics, Composites, Electronic materials, Nano-structured materials.
- Selection of Materials: Classification of carbon steel, low alloy, carbon molybdenum, ferritic, austenitic and martensitic stainless steel. Selection and application of advanced alloys, stainless steels, Cr-Mo steels, Ti-alloys
- Heat Treatment and Mechanical Testing of materials including standards and specifications: Mechanical properties of materials & their evaluations as per ASTM or equivalent standards, tension, hardness, creep, fatigue (low & high cycle) & impact toughness tests.
- Metal Forming, Welding Science & Technology: Metal fabrication technologies, rolling, forging, extrusion, deep drawing and introduction to material modelling. Welding metallurgy for stainless steels, ferritic steels, dissimilar metal welds and Ti-alloys, hard-facing and repair welding.
- Metallographic Examination: Experimental techniques for characterization of microstructure (Optical, TEM/SEM and microscopic techniques) specimen preparation and evaluation of microstructure of different materials.
- Corrosion: Galvanic, Uniform, Crevice, Stress corrosion cracking, Corrosion fatigue, Corrosion fast reactors and re-processing plants, Corrosion test methods and standards.
- Non-destructive evaluation techniques for materials and components: Visual, LPT, MPT, UT, Eddy current, X-ray Radiography, Neutron, Gamma ray etc. for quality assurance and in-service inspection.
- Nuclear Fuels: Production, fabrication, properties and application of nuclear fuels (metallic fuels, ceramic fuels (oxide, mixed oxide, mixed carbide)) and heavy water. Radiation damage and post irradiation examination of core materials.

Course Outcomes:

Students will understand classification and selection of engineering materials including carbon steels, stainless steels, Ti-alloys, polymers, ceramics, composites, and nuclear fuels. They will evaluate materials using heat treatment, mechanical testing (creep, fatigue, hardness, impact), metallographic examination, corrosion studies, welding metallurgy, and non-destructive evaluation techniques.

References:

1. Introduction to Materials Science for Engineers - James Shackelford
2. Physical Metallurgy Principles & Practice - V.Raghavan
3. Introduction to Solids - L.V.Azaroff
4. Structure and Properties of Materials - Wulff Series, Wiley Eastern, New Delhi
5. Materials in Nuclear Application - C.K.Gupta
6. Nuclear Chemical Engineering - Benedict and Pigford
7. Physical Metallurgy, Reed – Hill
8. Heat treatment of steel – Avener
9. Introduction to Solid State Physics - Charles Kittel (Wiley Eastern)
10. Physical Metallurgy: Principles and Practice - V. Raghavan (Prentice Hall)
11. The Physics and Chemistry of Materials - Joel Gersten and Fiedenick Smith (Wiley, Canada)
12. Fundamentals of Materials Science and Engineering - D. Callister (Wiley, Europe)

RP: Fast Reactor Physics and Shielding (35 Lecture Hrs)

Coordinators: Shri Rajeev Ranjan Prasad
(rajeevphy@igcar.gov.in)

Course Details:

- **NUCLEAR THEORY BASICS**

    - Properties of Nuclei: Size, shape and density of the nucleus, nuclear forces, nuclear structure, binding energy, stability of nucleus, radioactivity
    - Fission Process: Spontaneous and induced fission, liquid drop model, fission neutrons, delayed neutrons, fission gammas, fission products, fission product yield, FP mass asymmetry, formation and removal of FPs in a reactor
    - Concept of Nuclear Reactor: Fission energy, fission rate and reactor power, energy balance, fissile, fertile and fissionable materials, reactor materials: fuel, coolant, structure, control and shield, fission product activity after shutdown – decay heat, types of reactors
    - Interaction of Neutrons with Matter: Production of neutrons, elastic and inelastic scattering, radiative capture and their significance in reactors, production of photo neutrons, transmutation
    - Concept Cross-section: Microscopic and macroscopic cross-section, mean free path, Maxwell-Boltzmann distribution and its departure, structural changes caused by neutron reactions
    - Variation of Cross-section with Energy: Fast, resonance and thermal ranges, 1/v law of neutron cross-section, resonance absorption, Breit-Wigner formula, Doppler effect Capture to fission ratio, Eta vs E curve, conversion and breeding concepts, Thorium utilization

- **BASIC REACTOR PHYSICS-STATIC**

    - Diffusion of Neutrons: Fick's law and its validity, steady state neutron diffusion equation, concepts of neutron flux and current, interface conditions, diffusion coefficient, diffusion length and extrapolation distance
    - Chain Reaction: Four factor formula, conceptual treatment of diffusion of one group of neutrons in non-multiplying and multiplying media, infinite and effective multiplication factors, bare homogeneous reactor concepts, material and geometrical buckling, sub criticality and super criticality, critical mass, non-leakage probabilities in bare homogeneous cores, neutron cycle and life time in finite reactor
    - Slowing Down Process: Neutron Slowing down, slowing down power and moderating ratio of moderators, slowing down with spatial migration, Fermi age concepts, migration length, multi zone reactors, ideas of reflectors/blankets, reflector savings, form factor

- **TIME DEPENDENCE**

    - Reactor Kinetics: Time dependent neutron diffusion equation, one group kinetic equation, role of delayed neutrons, prompt neutron life time, point kinetic model to illustrate importance of delayed neutrons, reactor period, reactivity and its units
    - Core Burnup and Neutron Poisons: Burnup equations including fission products, Xenon and Samarium poisons, Xenon loads (operating and post shut down), variation of Xenon load with power and enrichment, Xenon oscillations and their control
    - Reactivity Coefficients and Reactor Experiments: Temperature and void coefficients of

reactivity, their relevance to reactor safety Techniques to control reactors, typical reactivity balance, long term burnup, fuel management, reactor control system – requirements of physics aspects, reactor shutdown mechanisms and neutron monitoring during operation and shut down Approach to criticality, physics measurements and calibrations/validations

- **FAST BREEDER REACTORS**

  - Introduction: Fast reactors as breeders, comparison of fast and thermal reactors, types of fast reactor, role of fast reactors in Indian nuclear power program
  - FBR Neutronics: Neutron spectrum, reaction cross-section, core characteristics, blanket characteristics, breeding potential, breeding ratio and breeding gain, doubling time, Multigroup diffusion theory methods and summary of steady state computational methods for FBR Effective delayed neutron fraction and prompt neutron life time, fuel expansion and bowing, sodium void reactivity effect, Doppler reactivity effect, long term reactivity effect - in FBR
  - FBR Core Design: General features of FBR core, specific power, linear rating, burnup, fluence, requirement and choice of core materials (fuel, coolant and structural materials), test reactors, commercial fast reactors, pin diameter, core height/diameter ratio, blanket thickness
  - Salient physics aspects of FBTR and PFBR
  - Reactor Shielding: Source of various neutron & Gamma radiation within the reactor system; Attenuation of neutrons & gamma rays; Dose rates for gamma rays for various source geometries; Buildup factors for homogeneous & multiple layer shields; Removal diffusion theory for neutron attenuation; coolant activation, heat generation. Streaming of radiation through gaps & void in the shield; description of various shielding arrangements of Indian reactors

Course Outcomes:

Students will understand nuclear structure, fission process, neutron interaction, cross-section behavior, and neutron diffusion theory in reactor systems. They will analyze reactor kinetics, burnup, delayed neutrons, breeding ratio, multigroup diffusion theory, sodium void and Doppler reactivity effects, and design radiation shielding using neutron and gamma attenuation concepts.

References:

1. S. Glasstone and S. Sesonske, Nuclear Reactor Engineering, Van Nostrand, 1963.
2. S. Glasstone and M.C. Edlund, Elements of Nuclear Reactor Theory, Van Nostrand, 1952.
3. J. R. Lamarsh, Introduction to Nuclear Engineering, Addision Wesley, NY, 1960.
4. M. El-Wakil, Nuclear Power Engineering, McGraw-Hill
5. P.P. Zweifel, Reactor Physics, McGraw-Hill, 1973.
6. Weston M. Stacy, Nuclear Reactor Physics, John Wiley & Sons, Inc.
7. A.E. Walter & A.B. Reynolds, Fast Breeder Reactors, Pergamon Press.

HP: Health Physics & Radiological Safety (25 Lecture Hrs)

Coordinators: Dr. S. Chandrasekaran
(schand@igcar.gov.in)

Course Details:

- Introduction: Radiation sources: Natural and Induced radioactive sources, units of radioactivity, half-life and decay constant, specific activity. Basic interaction mechanism of a) alpha b) Beta c) Gamma/X-rays d) Neutrons with matter. Definition of various dosimetric terms (exposure, absorbed/equivalent/effective dose, concept of radiation/tissue weighting factors and their importance (SI units & new units). Concepts of Exposure measurement: Free air and Air wall chambers, Exposure-dose relationship, Bragg-Gray principle.
- Biological effects of Radiation: Human body: Cells, tissues and organs, structure of cell, cellular effects. Factors, which influence the damage of cell. Interaction of radiation with biological matter. Radiation effects: stochastic and deterministic. Acute and delayed effects. Types of exposure (natural, occupational, medical and public).

- Radiation Protection and Regulations:
    - Importance of radiation protection program in DAE, Atomic Energy act, National and International regulatory bodies, their role and responsibilities., Radiation Protection Rules, Dose limits stipulated by these bodies. Dose limits observed in India.
    - Radiation protection philosophy, Principles of radiation protection, concept of ALI & DAC (with suitable problems). Fundamentals of ICRP respiratory model, entry through ingestion, GI track model.
    - Principles of radiation detection and monitoring: Basic operating principles of a) Gas b) Scintillation (including thermo luminescence detectors) and c) Semiconductors detectors.
    - Type of Radiation monitors/Radioactivity measurement methods adopted for radiation protection.

- Radiation protection and measurement (External and Internal):
    - Control of external exposures (with problems in each case).
    - Buildup concept, shielding from alpha, beta, gamma and neutron sources. Shielding from mixed sources.
    - Routes of intake of radioactive material,
    - Radiotoxicity and classification of laboratories, design of laboratory for radioactive work, Radioactive waste classification and management. Personal monitoring, area-monitoring, air monitoring. Bioassay, whole body counting techniques. Use of personal dosimeters (TLDs, pocket dosimeters)

- Radiation Protection procedures: Procedures followed in radiation work places, work permits, zoning concept, contamination control methods, and rubber areas, spill pack (gloves + absorbing paper), Decontamination techniques. Precautions during radioactive source storage and handling, safety during transportation. Nature of duties and responsibilities of Radiation Safety Officer/Health Physicist.
- Nuclear Accidents, Emergency Preparedness and Management: Reasons for accidents, classifications of accidents, International Nuclear Events Scale. Types of emergency, emergency preparedness.
- Radiological aspects and Environmental Impact of FBRs: Radiological aspects of Fuel Cycle Facilities
- Industrial Safety Aspects: Introduction to Industrial Safety (accident prevention technique, Job safety analysis, control measures), Factories Act, 1948 & Atomic Energy Factories Rules, 1996,ndustrial safety aspects (Physical and Chemical Hazards),Industrial safety aspects (safety in Machineries, hand

tools & Material handling equipments, personal protective equipments, etc)Construction safety (includes Electrical Safety & Work Permit System).

Course Outcomes:

Students will understand radiation sources, dosimetric quantities, interaction of alpha, beta, gamma and neutron radiation with matter, and biological radiation effects. They will apply ALARA principles, ICRP models, radiation monitoring techniques (gas, scintillation and semiconductor detectors), shielding methods, radioactive waste management, emergency preparedness, and regulatory safety standards.

References:

1. Introduction to Health Physics – Herman Cember
2. Introduction to Radiation Protection – Alan Martin
3. IAEA Regional Basic Professional Training Course on Radiation Protection (Course jointly organized by BARC and IAEA), October 26-Dember 18, 1998
4. Nuclear Radiation Detection - W.J. Price
5. Radiation Detection and Measurement - G.F. Knoll
6. Biological Effects of Radiation – J.E. Coggle
7. Nuclear Radiation Detectors by S.S. Kapoor and V.S. Ramamurthy (Publication: New Delhi, Wiley Eastern Ltd, 1986)
8. Atoms, Radiation and Radiation Protection by James E. Turner 1986
9. Problems and solutions in Radiation Protection by James E. Turner, 1988
10. Guide Lines for Hazard Evaluation Procedures – American Institute of Chemical Engineers
11. Risk Analysis in the Process Industries: The Institute of Chemical Engineers, England.
12. Loss Prevention in The Process Industries: Hazard Identification, Assessment and Control; Vol-1, 1996 2 Edition, Frank P Lees.

NR: Nuclear Reactors (50 Lecture Hrs)

Coordinators: Shri D.Nagasivayya
(dnsiva@igcar.gov.in)

Course Details:

- **Mechanical Aspects of Power Plant Engineering:**

  Basic thermal Cycle used in NPS, means of Improving cycle efficiency, Major components in thermal and Nuclear stations, Heat Balance typical calculations, Details of equipment – Steam Generators, Turbines, Condensers, Feed Water heaters, De-aerator feed pumps, condensate and other pumps: condenser cooling water system: C&I; steam pressure control, steam discharge and steam dumping features.

- **Thermal Power Reactors :**

  Layout of Nuclear Power Plant; Zoning requirements: layout of typical PHWR; description of layout in the reactor building; Special requirements for'; nuclear components regarding material selection, reliable operation with examples of pumps, valves, heat exchangers etc. operating environment (including capabilities to withstand seismic loads). Description of calandria, end shield and coolant channel (including fitting). Description of reactivity control scheme and related hardware e.g. zone control, regulating rods, absorbers, shutdown systems etc. Fuel and Fuel transfer system; Primary Heat Transport System; emergency core cooling system; Moderator system; Auxiliary System; Description of process Water, Fire Water and Ventilation system (emphasis on role played as safety support systems); Containment and associated safety systems to mitigate consequences of accidents and contain reactivity release; ultimate heat sink and heat removal paths.A brief overview of PWR, BWR and AHWR

- **Fast Power Reactors :**
  - Fast Reactor Physics and Safety: Role of FBR's, breeding ratio, doubling time, core design features - Static and Dynamic, control rod design, shielding principles, Fuel management, safety.
  - Overview of FBR: FBTR and PFBR. Comparison of FBRs: Core & important design parameters, comparison of core components, major primary and secondary system components.
  - Core Engineering: Description, choice of core materials, Engineering design of core, High temperature design methods.
  - Heat Transport Systems: Introduction, Design of IHX, SG, sodium pump, sodium piping, Decay heat removal system.
  - Instrumentation & Control: FBR instrumentation requirements, Neutronic Instrumentation and failed fuel detection methods, Reactor protection instrumentation and process instrumentation.

- **Sodium Technology**
  - Properties of Sodium: Physical and chemical properties, (Hazardous nature and sodium-air, sodium-water reactions), heat transfer properties, Manufacture of sodium, Heat transfer in liquid metals, Hartman effect in liquid metals
  - Sodium Systems – General Description: Components of a sodium system, process, cover gas system etc.
  - Impurities in Sodium, Purification Methods: Impurities in sodium, purification methods, impurity monitors, (plugging indicator, on-line hydrogen, oxygen and carbon monitors)
  - Sodium System: Components, piping and Quality Control Materials, design aspects, tanks, valves, vapor traps and other mechanical engineering aspects, sodium centrifugal pumps, high temperature piping for sodium, fabrication aspects, quality control
  - Sodium Pumps and flow meter: Electromagnetic pumps and flow meter for sodium systems
  - Electrical Systems for Sodium Loops: Electrical supply, heating systems, heater control, types of

power supply

- Instrumentation and Control: Level, leak, flow and temperature monitoring, pressure measurement, control of process parameter in sodium systems, under sodium viewing.
- System Operation Aspects: Sodium system pre-commissioning checks, methods of checking all components, limiting conditions of operation, surveillance checks etc.
- Sodium component cleaning, fire and safety
- Sodium removal and disposal methods, sodium fire and extinguishment methods, system and industrial safety aspects.

Course Outcomes:

Students will understand thermal cycles, steam generators, turbines, condensers, PHWR layout, reactor control systems, emergency core cooling systems, and containment safety features. They will analyze fast breeder reactor design, heat transport systems, sodium technology, neutronic instrumentation, failed fuel detection, and reactor protection systems.

References:

1. Nuclear Power Engineering, M. EI-Wakil, Mcgraw Hill Book Co., New York.
2. Steam Power Station, G.A. Gassort.
3. Power Plant Engineering & Economics, Strosal & Vapet.
4. Central Electricity Generating Board (London), Modern Power Station Practice, Nuclear Power Generation Ed 2, Oxford, Pergamon, 1971.
5. Weisman. J. Modern Power Plant Engineering, Englewood Cliffs, Prentice Hall, 1985.
6. IAEA Directory of Nuclear Reactors, Vol. IV, Power Reactors, Vienna.
7. Fast Reactor Technology: Plant Design, J. G. Yevick, M.I.T. Press.
8. Fast Breeder Reactors, A.E. Waltor & A.B. Reynolds, Permagon Press.
9. Status of liquid metal cooled fast reactor technology, IAEA-TECDOC—1083
10. Material for Sodium Technology portion will be provided during the course

RE: Reactor Engineering (40 Lecture Hrs)

Coordinators: Shri Sriramachandra Aithal
(saithal@igcar.gov.in)

Course Details:

- **Core design**
  - Introduction - Role of FBR, Main Characteristics of LMFBR, Sodium as coolant, Core Configuration, Definition of NSSS & BOP, Pool & Loop Type Design.
  - Fixing Size & Parameters of LMFBR - Test Reactor, Commercial & Prototype Reactor, Unit energy cost, Hot Spot temperature of Clad, Optimisation on Pin Diameter.
  - Definition of Smear Density, DPA & Burn up.
  - Fast Reactor Core – Fuel, Basic Requirements, Choice of fuel material, Candidates for Fuel, Swelling, Fabrication cost, Reprocessing, Negative Doppler coefficient, Thermal expansion, Burnup.
  - Absorber – required features, candidate materials
  - Structural Material in Core - Requirements of Core Structural Material, Effect of Neutron Irradiation on SS, Radiation Hardening, Embrittlement, Void Swelling, Irradiation Creep, Effect of Swelling & irradiation induced creep, Efforts to reduce swelling.
  - Sub-Assembly (SA) Design - Basis for Number of pins in a fuel SA, Pin spacers, Gas Plenum, Duct considerations, Volume Fraction, Assembly Length.
  - Other Subassembly design - Blanket, CSR, DSR, Reflector, Inner B4C, Outer B4C and Steel Shielding subassemblies.
  - Thermal Design of Fuel Pin - Thermal Analysis, Causes for fuel restructuring, Developing Analytical Model, Necessary physical parameters, Na Heat Transfer coefficient, Hot spot Analysis, Calculation of temperature distribution across fuel pin.
  - Mechanical Design of Fuel Pin - Failure Criteria for Pin, Strain Limit Approach, Cumulative Damage Fraction, Stress analysis, Cladding wastage.
  - Hydraulic Design of Core - Factors to be reviewed for Core Hydraulic Design - Hydraulic lifting force, Mixing studies, Power flattening & flow zoning, Vibration.
  - Handling of core subassemblies - Inherent problems associated with on-line fuel handling, Fresh SA Handling, Spent SA Handling.

- **Coolant circuits**
  - Selection of coolant for FBRs, thermal, transport, nuclear, chemical and other considerations. comparison between various coolants. Special characteristics of sodium. Its impact on heat transfer and structural mechanics considerations. Selection of structural materials, basis and important alloying elements.
  - Main heat transport system: primary and secondary sodium system, necessity of intermediate loop. Safety Grade decay Heat removal system, Decay heat, necessity for independent system.
  - Features of major components such as intermediate heat exchangers, steam generators, sodium to air exchangers, sodium pumps, electro magnetic pumps, sodium tanks, support design for sodium components from thermo mechanical and seismic considerations, sodium valves and types.
  - Design criteria, Loadings to be considered, Analysis method and validation methodology.
  - Special characteristic of sodium piping, sodium leak, sodium fire, various types of leak detectors, continuous and discontinuous level detectors etc.
  - Sodium purification loop, oxygen control, plugging indicator, cold trap, characteristics and features.
  - Operating experiences of fast reactors, failures and sodium leaks reported for Phenix,

Monju, PFR and other fast reactors, reasons for leak and remedy.

Course Outcomes:

Students will develop expertise in LMFBR core design, fuel selection, smear density, burnup, DPA, absorber materials, and structural material irradiation effects. They will analyze fuel pin thermal-mechanical design, hydraulic core design, sodium coolant circuits, intermediate heat exchangers, steam generators, decay heat removal systems, sodium purification, and reactor component safety considerations.

References:

1. Fast Breeder Reactors - Walter, A.E. & Reynolds, A.B., PERGAMON Press.
2. Fast Reactor Technology - Plant Design - Yevick, J.G., M.I.T. Press.
3. Fundamental Aspects of Nuclear Reactor Fuel Elements - Donald R. Olander, U.S.Department of Energy, 1985.

CORE COURSES

EL2: Reactor Control Engineering (20 Lecture Hrs)

Coordinators: Dr. V.L. Anuraj
(anuraj@igcar.gov.in)

Course Details:

- Physics of Reactor Control
- Reactor Kinetics – Point kinetic model, reactor response to step and ramp reactivity inputs, stable reactor period.
- Reactor as a control element: basic zero energy state space model and transfer function, feedback loop transfer functions, effect of temperature and voidage, poisoning due to xenon and samarium, fuel burn-up, reactor system stability analysis from transfer function and state space model. Manual and computer control.
- Large reactor control: Neutronically decoupled cores. Modeling techniques for large reactors-modal, nodal and quasi-static methods (introduction only) flux tilt and spatial instability.
- Typical reactor control system: BWR, PWR, PHWR, Fast Reactor, research reactor and 235MWe PHWR, FBTR and PFBR.
- Reactor operation: Approach to criticality, re-start up, operation in power range, shut down.
- Power plant control: Power plant programming. Constant T_{av} program, constant pressure program, boiler level and pressure control. PHT pressure control. Pressuriser pressure and level control. Secondary circuit and feed water control.

Course Outcomes:

Students will understand reactor kinetics, reactivity feedback mechanisms, and stability analysis using transfer function and state-space models. They will be able to analyze and compare control strategies and control systems of different reactor types during various operational states.

References:

1. Nuclear reactor physics – W.M. Stacey. John Wiley and sons. 2001.
2. Nuclear reactor kinetics – Ash. M. Mcgraw Hill, Newyork, 1979.
3. Nuclear reactor kinetics and control, Weaver. L.E. American Elsevier, 1968.
4. Optimal control of nuclear reactors, Mohler.R.B. and Shen.C.N., Academic Press. 1970.

EL3: Nuclear Instrumentation (20 Lecture Hrs)

Coordinators: Dr. N. M. Meenachi
(meenachi@igcar.gov.i)

Course Details:

- Fundamental considerations/philosophies, requirements and scope-Reactor and Health Physics Instrumentation
- Principles of detection and types of radiation detectors: in-core and out – of –core. Consideration in reactor start-up (cold & hot) and normal operation, GM counters, Scintillators, Gamma Ion chambers
- Detector signal conditioning (Pulse, Campbell and DC modes) and generation of logarithm & period signals
- Block Schematics of Pre-amplifier, Count rate meters, Nuclear ADCs, MCA, Low-voltage and High voltage Power supplies, Scalar timers.
- Introduction to various reactor instrumentation and radiation monitors:
- Start-up, Intermediate and Power Range Instrumentation, Reactor Regulating System, Flux Mapping System, Failed Fuel Detection System, Stack Monitoring System, Area Gamma and Neutron Monitors, Contamination Monitors, GM Survey meters, Gun monitors, Neutron REM monitors, RADAS

Course Outcomes:

Students will gain knowledge of radiation detection principles, detector systems, and signal processing techniques used in nuclear reactors. They will be able to understand reactor instrumentation systems for startup, power operation, and radiation monitoring applications.

References:

1. Radiation Detection and measurement -G.F. Knoll
2. Nuclear Electronics - P.W. Nicholson
3. Selected topics in Nuclear Electronics, IAEA-TECDOC-363 (CC library Acc no: 123583)
4. Nuclear Power Reactor Instrumentation Systems Handbook, Vol: 1 J.M. Harrer, J.G. Beckerly
5. The Technology of Nuclear Reactor Safety Vol1, T.J. Thompson, J.G. Beckerly.

EL4: Reliability Engineering (20 Lecture Hrs)

Coordinators: Dr. M. Ramakrishnan
(mramki@igcar.gov.in)

Course Details:

- **Introduction: Reliability Engg. Applied to C&I Systems**

  Explain the course coverage and the general issues related to the reliability and safety of the current C&I Systems. The reliability of computer based C&I system as a function of circuit hardware, software and human errors experienced in the NPPs and research reactors.
  Terms and definitions with adequate explanation and giving examples from electrical, electronic and computer based systems.
  Quality, Reliability, Availability, Maintainability and supportability, MTBF, Failure and hazard rates, CCF, CMF, Failure Modes, FMEA, FMECA, Fault tolerance, Confidence and Risk Factors etc.

- **Reliability Maths/Statistics:**
  - Mathematical and statistical expressions required for reliability study.
  - Types of failures in electrical, electronic and computer components
  - Failure probability concept, statistical distribution models_
  - Binomial, Poisson, Exponential, Normal, Lognormal, Weibull distributions
  - Chi-square distribution and its use in confidence and risk factors
  - Baye’s theorem
  - Reliability or life characteristics of hardware electronic circuit components, and comparison with the characteristics of mechanical/electro-mechanical components and computer software.
  - Bath-tub curve and explanation of different parts of the life characteristic curve, and corresponding failure distributions.
  - Derivation of exponential reliability expression_
  - R(t)=[exp-(lt)] for electronic components and systems.
  - Examples to solve

- **Fault Tolerance and Systems Reliability:**
  - Fault tolerance concept for electronic and Computer based C&I systems.
  - Circuit hardware redundancy concept to enhance system reliability, types of redundancy_
  - Series, parallel, active, passive, and voting redundancy
  - Redundancy and other fault tolerance methods for software
  - FMEA, FMECA concepts for C&I and Examples to solve
  - Concepts for the analysis of System Reliability, availability, and maintainability.
  - System reliability and availability analysis methods:
  - Boolean logic
  - Digraph, cutest-tie set method
  - Fault tree model, and consideration of CCF, CMF, software errors
  - Markov Model
  - Example from C&I system in the NPPs

- **QA/QC Concepts in Brief:**
  - QA/QC Concepts in the components, systems procurement, manufacture and
  - Site installation for C&I systems in the NPPs.

- **Environmental Qualification and Reliability Testing:**

- Environmental qualification, testing of the C&I systems.
- Effects of various environments on the electrical/ electronic components
- Climatic Qualification tests: Temperature, Humidity
- Special environments: EMI/EMC tests on C&I Systems, Gamma radiation/LOCA Qualification tests
- Reliability Testing of the electronic components, equipment and C&I systems.
- Reliability screening tests for electronic components
- Accelerated environmental tests
- Failure terminated and time terminated tests
- Estimation of MTBF (q)/Failure Rate(l) of electronic components and systems using c2 distribution for confidence level.
- Few examples to solve

- **Additional safety concepts:**
  - Defense-in-depth, fail-safe concepts in the design of C&I, and other safety critical systems in the NPPs.
  - Single failure criteria, engineered safety systems in the NPPs
  - Safety Classification and Seismic categorization of C&I Systems
  - Target reliability goals, reliability allocation to safety systems as per their safety importance in the NPPs
  - Reliability and safety aspects for the integrated C&I systems
  - (hardware, software, human errors considerations)
  - IEC, IAEA, AERB, IEEE standards relevant to C&I in the NPPs
  - Human Factors (man-machine interface) reliability, and human reliability issues in the NPPs
  - Current research topics in reliability and safety analysis such as Fuzzy Logic, Neural Network Methods

- **PSA/PRA Concepts in NPPs:**
  - Probabilistic Safety (Risk) Assessment: PSA/PRA methods or safety/ risk assessment in the NPPs.
  - Explain Event Tree
  - Fault-Tree-Fault Tree method for risk assessment in terms of core damage frequency.
  - Level-1, Level-2, Level-3 PSA studies (Brief introduction only).

Course Outcomes:

Students will understand reliability, availability, and safety concepts applied to nuclear C&I systems using statistical and analytical methods. They will be able to perform reliability modeling, fault analysis, and apply PSA/PRA concepts for nuclear power plant systems.

References:

1. Reliability Engineering for Nuclear and other High Tech Systems By Lakner and Anderson, Elsevier Applied Sci. Publ. (1985)
2. Reliability Engineering for Electronic Systems By R.H. Mayers et al, John Wiley, NY (1964)
3. Practical Electronics Reliability Engg By Jerome Klion, Van Nostrand, NY (1992)
4. Reliability and Risk Analysis By Norman J McCormick, Academic Press (1981)
5. Fault Tolerant and Fault Testable Design By Parag K. Lala, Prentice Hall, (1985)
6. Dependability of Critical Computer Systems, Vol.1&2 By F.J. Redmill, Elsevier Applied Sci. Publ. (1988)
7. An Introduction to Reliability and Maintainability Engg By Charles E. Ebeling, Tata-McGraw Hill Publ. (1997)
8. Reliability Technology By A.E. Green and Bourne, UKAEA, John-Wiley (1972)
9. IEC Standards: 880, 987, 1225, 1226 on C&I Systems
10. AEA Safety Standard/Guide G:1.3, Instrumentation & Control for the safety of Nuclear Power Plants (2002)

11. IAEA-TECDOCS: 780, 790 on Computer based C&I Systems.
12. MIL-Std-217F: US Military Handbook: Reliability Prediction of Electronic Equipment (1993)
13. Reliability of Computer and Control Systems by Viswanadham et al, North-Holland/ Elsevier Publ.(1987)
14. Software Reliability Methods, by Doron A.Peled (Bell/Lucent Labs), Springer Publisher (2001), (‘Formal Methods’ has been explained).
15. Handbook of Reliability Engg Ed. Igora Ushakov & R. Harrison John Wiley & Sons (1994)
16. Burn-in by Fenn Jenson Failure Models by I.B. Gertsbakh
17. System Reliability_ Concepts & Applications by K.B. Klassen (1989).

EL5: Software Engineering (20 Lecture Hrs)

Coordinators: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- Introduction: Importance of software engineering, software characteristics, life cycle and models, phases, processes, work- products of different phases
- Analysis and Design I: Data models, Functional modeling, structured analysis and design, design attributes and metrics, CASE tools.
- Analysis and Design II: Object oriented methods, Unified Modeling Language (UML), notion of objects, classes, attributes, methods, interfaces, associations, generalization, composition, polymorphism. Modeling structure and behavior, Use case diagrams, class diagrams, state diagrams, sequence diagrams, architectural and detailed design., Modeling real-time software. Introduction to Object Oriented Languages. CASE tools.
- Software Quality Assurance: Quality attributes, metrics, reliability, SQA activities.
- Verification and Validation: Reviews, inspection and walk-through, Static analysis, formal methods. Testing principles, unit testing, Integration testing, acceptance testing., Unit testing: black box testing, white box testing – coverage criteria, Equivalence class partitioning, boundary value testing.
- Software Configuration Management: Configuration items (with examples), baselines, libraries, version control.
- Software Engineering Standards.

Course Outcomes:

Students will understand software development life cycles, analysis, design methodologies, and quality assurance practices. They will be able to model, design, test, and manage software systems using structured and object-oriented techniques.

References:

1. Software Engineering by Roger S. Pressman, McGraw Hill International Students Edition.
2. Software Engineering by Ian Sommerville, 5th Edition, Addison Wesley.
3. An Integrated Approach to Software Engg. by P. Jalote, Springer/Narosa Publishers.
4. Unified Modeling Language User Guide by G. Booch, J. Rumbaugh, I. Jacobson, Addison Wesley.
5. Real-time UML, second edition, Bruce P. Douglass, Addison Wesley.

EL8: Human Machine Interface for Reactor Control Instrumentation (45 Lecture Hrs)

Coordinator: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- **Reactor Instrumentation**
  - Instrumentation for design of Reactor Regulating System and Reactor Protection System: Introduction to Reactor Protection System and Reactor Regulating System: Elements in RPS/RRS, from sensor to Reactor Protection/Control Devices, Design Principles, Typical list of Reactor Trip parameters, Seismic qualification, Class-1E qualification, EMI/EMC qualification.
  - RPS & RRS for FBRs : Core Temperature Monitoring System, Diversified Safety Logics, Control Logics for CSRDM & DSRDM.
  - Supervision Systems : Startup systems, Discordance supervision systems for SCRAM signals & CSRs, Alarm Generation system, ESR & PDA.
  - Component Handling Systems: I & C for Rotatable plugs, Transfer Arm, IFTM, CTM, Under Water Trolley and Storage Bays, HMI in HCR for Component handling and fuel movement monitoring.
  - Relay & Control Interlock Logic Circuits: Relay Terminology and general application: Criteria for relay selection, Pickup, hold and dropout voltage, Contact type and arrangement, Contact protection, latched relay, Electromechanical versus Solid-State Relay characteristics and comparison. Typical control logic circuits for control of process equipments, low selector, high selector, median selector, voting logics, Interfaces with electrical Control gear.
  - C & I Cables : Types of cables, Conductor materials, insulating materials, Sheath materials, Shielding, armouring, FRLS and Fire Survival cable, mineral insulated cables, cable sizing, noise reduction, cable layout, cable trays, panel wires, conductor identification, Cable Testing, wiring practices.
  - Incident monitoring & mitigation systems : RCB Isolation, I&C for SGDHR, Seismic Instrumentation, Post Accident monitoring system, Video monitoring system.
  - Special systems: Fire Alarm System, Physical protection systems, Biometric Sensors, etc.
  - Distributed Control System (DCS) and Computer Based Systems: Distributed Process Control, DCS configurations, Components of DCS, Data Highways, Human machine interface, Operator Stations, Presentation of information on operator station, DDCS for PFBR. Programmable Controllers (PLC) - Basic PLC architecture, PLC Programming Languages, Typical PLC Specifications, Redundant PLC architectures, relevant communication protocol and standards, PLCs for package systems.
  - PC based process control system, Supervisory Control and DATA Acquisition System (SCADA), Features of SCADA software, SCADA for substation. Concept of Fieldbus, fieldbus standardization, Industrial networks and Protocols.
  - Control Room, Control Panels and Cabinets : Conventional control rooms, Modern control rooms, Control room layout, Environmental specifications for control room, Control room lighting, Control room cabling, Communication systems for control room. Control Panels- Panel types, Panel layout, Panel construction materials, Human Engineering principles in control room and panel design- relevant standards (EPRI; NUREG), Components of control panel, Panel wiring, Power distribution in panels, Wiring and terminal identification. Control Cabinets- Sizes, Materials, Degrees of environmental protection, EMI & EMC protection, Standard accessories for mounting and cable routing. Seismic qualification of control panels and cabinets. Alarm Annunciation System-Functions of alarm annunciation; Types of annunciation (audio/visual); Alarm Sequences; applicable standard (ISA S18.1); Modern alarm displays; Grouping and Coding of alarms.

- **Human Machine Interface (HMI)**
  - Overview of plant automation.

- Design of HMI, Soft Console versus Conventional control panels.
- Guidelines for design of HMI displays.
- Case study of a commercially available Professional HMI package.
- Building HMI systems, Creating and using process databases, managing databases, Implementing an alarm strategy, Configuring and displaying alarms and messages, Security features, Creating process mimics, Trending historical data, Methods of passing data to HMI package.
- Practical.

Course Outcomes:

Students will understand the design principles of HMI systems for reactor control and protection systems. They will be able to design and evaluate control room layouts, alarm systems, and operator interfaces based on human engineering standards

References:

1. Intellution I fix documentation.
2. NPC Guidelines for development of soft consoles.

EL10: Modern Control of Dynamic Systems (30 Lecture Hrs)

Coordinator: Shri Kalyana Rao Kuchipudi
(kalyan@igcar.gov.in)

Course Details:

- State Variable Descriptions Introduction, The concept of state, Elementary definitions, state space representations of continuous-time and discrete-time systems, State diagrams, illustrative examples, solutions of state equation, state transition matrix, computation methods of state transition matrix, relationship between state equations and transfer functions, characteristic equations.
- Controllability and Observability: Introduction, definitions of Controllability and Observability, Controllability and Observability tests, Kalman Controllability Criteria, Principle of Duality, Controllability and Observability of discrete – time systems.
- Control System Design: Introduction to state feedback, Controller design using pole placement technique, Stabilizability, LQR technique.

Course Outcomes:

Students will understand state-space modeling, controllability, observability, and modern control techniques. They will be able to design state-feedback controllers using pole placement and optimal control methods.

References:

1.John J.D'Azzo and C.H.Houpis, "Linear Control System Analysis and Design- Conventional and Modern", 2nd Ed. McGraw Hill Book Co.1986.
2.Chi-Tsong Chen, "Linear System Theory and Design", CBS College Publishing, Holt, Rinehart and Winston, 1984.
3.M.Gopal, "Modern Control System Theory", 2nd., Wiley EasternLtd.,1993.
4.Gene F. Franklin et al, "Feedback Control of Dynamic Systems", 3rdEd., Addison-Wesley Publishing Co. 1994.
5.B.Friedland, "Introduction to State-space methods".
6. K.Ogata, "Modern Control Engineering", Prentice- Hall.
7. H.Kwakarnaak, R.Sivan-"Linear Optimal Control Systems"-Wiley interscience
8. D.G.Schultz,James.L.Melsa- "State Function and linear control systems"- McGraw Hill

ELECTIVE COURSES

EL6: Artificial Intelligence and DSP (40 Lecture Hrs)

Coordinator: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- **Introduction to Artificial Intelligence**
  - Introduction – Nature of AI problems.
  - Search – State space search.
  - Robotics – Kinematics and dynamics.
  - Knowledge Representation – Predicate logic.
  - Neural Networks – Feed forward vs Feedback.
  - Fuzzy Logic – membership functions.
  - Reinforcement Learning – Intelligent agents.
  - Genetic Algorithm – Solution representation.
  - Engineering applications including in Robotics.

- **Digital Signal Processing**
  - Introduction: Basic elements of a digital signal processing system, Fourier series and Fourier transform, z-transform, convolution, correlation, sampling theory, aliasing, anti-aliasing filter, quantization noise, signal reconstruction.
  - Discrete Fourier Transform: Interpretation of DFT, properties of DFT, DFT of real signals, periodic & linear convolution and correlation using DFT.
  - Fast Fourier Transform: Efficient computation of DFT using decimation-in-time and decimation-in-frequency algorithms, computation of Inverse DFT using FFT algorithm, efficient computation of the DFT of two real sequences and a 2N-point real sequence, spectrum analysis using the FFT, windows in spectrum analysis, use of FFT algorithm in linear filtering and correlation.
  - Digital filters: FIR and IIR filters, design techniques for FIR and IIR filters, realization of FIR and IIR systems, overview of DSP processors.
  - DSP Applications: Applications of digital signal processing in nuclear and other fields.

Course Outcomes:

Students will gain foundational knowledge of artificial intelligence techniques and digital signal processing concepts. They will be able to apply AI methods and DSP algorithms to engineering and nuclear instrumentation problems.

References:

1.Johnny R. Johnson, Introduction to Digital Signal Processing, Prentice- Hall of India,2000.
2.John G. Proakis and Dimitris G. Manolakis, Digital Signal Processing- Principles, Algorithms and Applications, Prentice- Hall of India,1995.
3.Allan V. Oppenheim and Ronal W. Schafer, Digital Signal Processing, Prentice- Hall of India,1988.

EL9: Embedded & Computer based systems Design (45 Lecture Hrs)

Coordinator: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- **Microprocessor Based Hardware Design:**
  - Overview of Microprocessors: Comparative study of Intel and Motorola family microprocessors (80186, 80486, Pentium series, 68XXX), Overview of 16 bit Microcontrollers (e.g. 80196), DSPs (e.g. TMS320, SHARC family) and ARM processor.
  - Personal Computers: Architectures, Memory organization, Industrial PC, Embedded PC.
  - Industry Standard Bus Systems: ISA, PCI, VME: Mechanical, electrical, functional & procedural specifications, multi-processing, bus arbitration, plug & play.
  - Design Case Study: Single board computer architectures, circuit design, and logic design, application of FPGA and CPLDs, ac/ dc analysis, timing analysis, thermal, EMC and signal integrity analysis. Design accommodations for testability, reliability and maintainability. Physical design and design tools.
  - IO board design, bus interface (ISA, PCI), FIFO and shared memory interfaces, Analog and Discrete IO interfacing, signal conditioning, isolation and protection issues, testability.
  - Embedded computer system design example.

- **Computer Communication and Networks**

  Asynchronous & synchronous communication standards, RS232C, RS485, USB, encoding (NRZI, Manchester), Modems, SDLC, Local area networks, Ethernet, Token passing principles, TCP/ IP, Fibre optic communications for LANs, wireless LANs (WAP, Blue tooth), Industrial networks, Field bus standards, Real-time issues in networking, Networking hardware (cables, hub, switch, routers etc.)

- **Fault Tolerant and Distributed Architectures**
  - Principles of fault tolerance, Hot- standby and Triple Modular Redundant (TMR) configurations, software implemented fault tolerance, reliability, and availability and safety issues.
  - Principles of distributed systems, architectures, Distributed control systems, Impact of Internet technology, Web enabled devices.

- **Real-Time System Design**
  - Real-time system concepts, Timeliness Vs speed, hard Vs soft real time systems, scheduling methods, concurrency, process and thread concepts, inter process communication and synchronisation, Case study of Real Time Operating Systems, development tools, real time programming, device drivers. Validation and performance evaluation of Real-time systems.
  - Overview of LINUX and Embedded NT.

Course Outcomes:

Students will understand the architecture and design of embedded and computer-based control systems. They will be able to design hardware–software integrated systems with communication, fault tolerance, and real-time constraints.

References:

1. Microprocessor and interfacing: D. V. Hall – McGraw Hill.
2. The Advanced Intel Microprocessors: 80286, 80386, 80486: Barry. B. Brey, - McGraw Hill.
3. Microprocessor, Micro-controller and DSP Handbooks: Motorola, Intel, Texas Instruments, Analog

Devices.
4. Hardware Bible: W.L Rosch- Tech Media.
5. VME Bus specifications: IEEE 1014- 1987.
6. Embedded System design – A Unified hardware/ software introduction: Frank Vahid / Tony Givargis – John Wiley and sons.
7. Computer networks: A.S. Tanenbaum, Prentice Hall.
8. Internetworking with TCP/ IP: Vol I to III: D.E.Comer, Prentice Hall.
9. Complete guide to networking: P. Norton & Kearns – Tech Media.
10. 10.Wireless communication & networks: W. Stallings – Pearson education.
11. 11.Fault-tolerant computing – Theory & Techniques: D.K. Pradhan (Ed), Vol I & II – Prentice Hall.
12. 12.The theory and practice of reliable system design: D.P. Siewiorek & R.S. Swarz, Digital press.
13. Modern Operating Systems: Andrew S Tanenbaum, Prentice Hall.
14. Distributed Operating systems: A .S. Tanenbaum – Pearson education.
15. Windows NT device driver development: P.G. Viscarola & W. Mason – Tech Media.
16. Real-time systems: Jane W.S. Liu – Pearson education Hill.

EL7: Process Instrumentation (35 Lecture Hrs)

Coordinator: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- Design, selection, typical specifications, calibration standards, installation, testability and diagnostics of measuring instruments of following process variables:

- Flow: Differential pressure flow elements: Orifices, venturies, flow nozzles, pitot tube, annubar, elbow flowmeter. Different standard pressure taps for orifices, sizing calculations, straight length requirements. Applicable codes for design of Orifices , venturies and flow nozzles. Orifice flanges, Jackscrews, carrier rings, flow straighteners, square root extractors, flow totalisers. Variable Area Flowmeters- Glass tube rotameters; Armoured rotameters; Bypass rotameters; Density correction factors. Magnetic, Turbine, vortex flowmeter; Ultrasonic flowmeters- transit time, Doppler type, Clamp on type ultrasonic flowmeters, Coriolis and thermal mass flowmeters, air velocity meters. Applications and limitations of various flowmeters. Two phase flow measurements.

- Temperature: Thermocouples- Types of thermocouples, ranges, sensitivity and their limits of error and applications, mineral insulated thermocouples, types of hot junctionsgrounded, ungrounded and exposed junction, thermocouple extension and compensating cables, high temperature thermocouples, cold junction compensation techniques. Applicable standards. RTDs- Wire wound and thin film RTDs, limits of error, self heating error, matched pair of RTDs. Applicable standards for RTD. Thermistors - performance and applications. Thermowell - Design considerations, Applicable design code for thermowell, thermowell installation aspects. Surface temperature measurement techniques.

- Temperature transmitters- Head mounted temperature transmitters, isolated temperature transmitters, Smart temperature transmitters. Radiation thermometryOptical pyrometer, total radiation pyrometer, two colour pyrometer, factors affecting the performance of radiation pyrometers.

- Pressure: Manometers-U tube, well and inclined manometers, pressure gauges, hydraulic and pneumatic dead weight testers- ranges and factors affecting the performance of dead weight testers. Pressure Transducers and transmitters- strain gauge, capacitance, LVDT, piezo-resistance type and piezoelectric type pressure transducers, transmitters with remote diaphragm seal, high temperature pressure transducers, Smart pressure and differential pressure transmitters. Vacuum measurement- Pirani and thermocouple gauges, cold cathode and hot cathode ionization gauge, Mcleod gauge.

- Level: Hydrostatic pressure and differential pressure methods, wet legs- cold reference leg and hot reference leg, condensing pots, density compensation in boiler level measurement, zero elevation and zero suppression. Gauge glass, Purge system, capacitance probes, displacer, ultrasonic, nucleonic, hydra step level gauge and radar level gauge. Level switches- conductivity, capacitance, ultrasonic, displacer, float type.

- Analytical Instrumentation: Conductivity, pH, ORP , Turbidity dissolved oxygen, silica and sodium Measurement. Other Measurements: Moisture, Relative humidity; viscosity and density measurement Turbovisory Instrumentation: Measurement of speed, vibration, differential expansion, overall expansion, eccentricity, Governor valve position, CIES valve position, Speeder-gear & load limiting gear position.

- Sodium Instrumentation: Properties of sodium-special requirement of sodium Instrumentation-sodium flow measurement- Magnetic flowmeter, Eddy current flowmeter sodium level measurement-continuous-discrete-resistance type-mutual inductance typeSodium Leak Detection-spark plug type & wire type leak detection-Sodium aerosol detection - Mutual Induction type leak detectors - Steam Generator Leak Detection systems-Hydrogen in sodium detection- Nickel diffuser based detection-Electrochemical meter based detection-Hydrogen in cover gas (argon) detection- Failed fuel detection system-Gammatography etc.,

- Signal Conditioning Circuits: Operational amplifiers-instrumentation amplifiers-signal linearization techniques, isolation amplifiers-two port-three port isolation.

- Control and Instrumentation Power Supplies: Class I, II, III, IV power supplies, Centralized 24V/48V DC power supply, Linear and switching mode power supplies, Fault Tolerant Dual redundancy power supplies, distributed power supplies, quality of power supply, Isolation transformer, grounding/earthing aspects in C & I systems.

- Reliability principles, Fail safe design principles, Diversity, active and passive redundancy, availability, maintainability, MTBF, MTTR, preventive-predictive-proactivecorrective maintenance-spares inventory control principles, Condition Monitoring etc.

Course Outcomes:

Students will understand the principles, selection, installation, and calibration of process measurement instruments. They will be able to apply instrumentation techniques for flow, temperature, pressure, level, analytical, and nuclear process measurements.

References:

1. Principles & practice of flow meter Engineering by L. K. Spink. The Foxboro Company.
2. Fluid Meters. ASME publication.
3. Manual on the use of thermocouples in Temperature Measurements (ASME Publication by subcommittee 4).
4. Measurement Systems: Application and Design, Ernest O Doeblin.
5. Process Control Systems: Application, Design and Tuning, F. G. Shinskey, Mcgraw Hill.
6. Applied Instrumentation in the Process Industries, Volume I & II, Edited by W.G. Andrew.
7. Process Control Engineering, M. Polke.
8. ISA Handbook of Control Valves, Editor-in-Chief J. W. Hutchison.
9. British Standard Code of practice for Instrumentation in Process Control Systems: installation design and practice (BS 6739).
10. Handbook on Applied Instrumentation: Edited by D.M. Considine and S.D. Ross, Mcgraw Hill.
11. Process Instruments and Control Handbook: Edited by D. M. Considine, Mcgraw Hill.
12. Instrment Engineer’s Handbook, Part I & II: Edited by Bela G Liptak, Chilton Book Company.
13. Instrumentation in the Processing Industries Edited by Bela G Liptak, Chilton Book Company.
14. IEC standard 61131.3 - PLC Programming Languages.
15. Human Factors in Control Room Design - EPRI NP 1118 / EPRI NP 3659.
16. NUREG-700 Guidelines for Control Room Design Reviews, U.S. Nuclear Regulatory Commission.
17. Eight Open Net works and Industrial Ethernet, (www.industrialethernet.com).
18. Basics of Fieldbus, Rosemount Inc. (www.rosemount.com)
19. MIL-STD-1553B Standard.

EL11: Analytical Instrumentation (25 Lecture Hrs)

Coordinator: Dr. K. Sundararajan (sundar@igcar.gov.in)

Course Outcomes:

Students will understand analytical measurement techniques based on spectroscopy, mass spectrometry, thermal, and electroanalytical methods. They will be able to interpret analytical data and understand computer-based automation in analytical instrumentation.

Course Details:

- **Measurement related issues**
  - Sensitivity, detection limit, signal-to-noise ratio enhancement
  - Absorption and Emission Spectroscopy
  - UV-VIS-IR Spectrophotometry
  - Atomic Absorption Spectrophotometry IR absorption methods for detection of Carbon, Sulphur, Oxygen, Nitrogen
- **Fluorescence Spectrometry**
  - Generation of X-Rays
  - X-Ray Fluorescence Spectrometry
  - X-Ray Diffraction Spectrometry
  - Laser florescence
- **Mass Spectrometry**
  - Applications and importance of mass spectrometry
  - Various types of ion sources
  - Various types of mass analysers
  - Various methods of detection
  - Computer based automation and measurements
- **Thermo analytical methods**
  - Thermal analysers-DTA and TG
  - Differential Scanning Calorimeters
- **Electro analytical instruments**
  - Voltametry, amperometry and Coulometry
  - Conductivity and Ph

References:

1. Instrumental methods of analysis, - Willard & Others, Pub: CBS, New Delhi, 7th Ed.
2. Principles of instrumental analysis, - Douglas A.Skoog and James J. Leary, Saunders College Publishing, Harcourt Brace College Publishers. (IGCAR Acc. No. 063944)

DETAILED COURSE STRUCTURE

Foundation Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	MM	Materials and Metallurgy	25	1
2.	RP	Fast Reactor Physics & Shielding	35	2
3.	HP	Health Physics and Radiological Safety	25(15 T+10 L)	1
4.	NR	Nuclear Reactors	50	3
5.	RE	Reactor Engineering	40	2
FOUNDATION TOTAL			**175**	**9**

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	FRE4	Reliability Engineering	20	1
2.	FRE5	Process Design and Control	30	2
3.	FRE8	Emergency Preparedness and Disaster Management	20	1
4.	FRE15	Reactor Control Engineering	30	2
5.	FRE16	Nuclear Instrumentation	25	1
6.	FRE17	Embedded System Design & Human Machine Interface	45	3
7.	FRE18	Process Instrumentation	45	3
CORE TOTAL			**215**	**13**

Electives (any four)					
Sr. No	**Course Code**	**Subject Title**	**Hours**		**Credits**
			(T)	**(L)**	
1.	FRE9	Plant Control	25	-	1
2.	FRE10	Turbine Generator Fundamentals	25	-	1
3.	FRE11	Mechanical and Electrical Equipments	25	-	1
4.	FRE12	Maintenance Engineering	25	-	1
5.	FRE13	Regulatory Framework for NPPs	25	-	1
6.	FRE14	Practicals	6 Weeks	-	12
ELECTIVES TOTAL			**125**	**-**	**17**

FOUNDATION COURSES COORDINATOR

Course	Coordinators	Contact
MM: Materials and Metallurgy	Dr. Vani Shankar	21147/22805,vani@igcar.gov.in
RP: Fast Reactor Physics and Shielding	Shri Rajeev Ranjan Prasad	22737,rajeevphy@igcar.gov.in
HP: Health Physics and Radiological Safety	Dr. S. Chandrasekaran	23556.schand@igcar.gov.in
NR: Nuclear Reactors	Shri D.Nagasivayya	21232,dnsiva@igcar.gov.in
RE: Reactor Engineering	Shri Sriramachandra Aithal	22468/22605,saithal@igcar.gov.in

CORE COURSES COORDINATOR

Course	Coordinators	Contact
FRE4: Reliability Engineering	Dr. M. Ramakrishnan	22611/22254,mramki@igcar.gov.in
FRE5: Process Design and Control	Dr. K. A. Venkatesan	22631/26857, kavenkat@igcar.gov.in
FRE8: Emergency Preparedness and Disaster Management	Dr. Vidya Sundararajan	22474/22454, vidya@igcar.gov.in
FRE15: Reactor Control Engieering	Dr. V.L. Anuraj	21537/22907,anuraj@igcar.gov.in
FRE16: Nuclear Instrumentation	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
FRE17: Embedded and Computer Based Systems Design	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in
FRE18: Process Instrumentation	Dr. N. M. Meenachi	21255/21253, meenachi@igcar.gov.in

ELECTIVES COURSES COORDINATOR

Course	Coordinators	Contact
FRE9:Plant Control	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE10:Turbine Generator Fundamentals	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE11:Mechanical and Electrical Equipments	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE12:Maintenance Engineering	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE13: Regulatory Framework for NPPs	Dr.S. Chandrasekaran	23556, schand@igcar.gov.in
FRE14:Practicals	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in

FOUNDATION COURSES

MM: Materials and Metallurgy (25 Lecture Hrs)

Coordinator: Dr. Vani Shankar
(vani@igcar.gov.in)

Course Details:

- Classification of Materials: Structure, Ferrous and non-Ferrous metals, Polymers, Ceramics, Composites, Electronic materials, Nano-structured materials.
- Selection of Materials: Classification of carbon steel, low alloy, carbon molybdenum, ferritic, austenitic and martenistic stainless steel. Selection and application of advanced alloys, stainless steels, Cr-Mo steels, Ti-alloys
- Heat Treatment and Mechanical Testing of materials including standards and specifications: Mechanical properties of materials & their evaluations as per ASTM or equivalent standards, tension, hardness, creep, fatigue (low & high cycle) & impact toughness tests.
- Metal Forming, Welding Science & Technology: Metal fabrication technologies, rolling, forging, extrusion, deep drawing and introduction to material modelling. Welding metallurgy for stainless steels, ferritic steels, dissimilar metal welds and Ti-alloys, hard-facing and repair welding.
- Metallographic Examination: Experimental techniques for characterization of microstructure (Optical, TEM/SEM and microscopic techniques) specimen preparation and evaluation of microstructure of different materials.
- Corrosion: Galvanic, Uniform, Crevice, Stress corrosion cracking, Corrosion fatigue, Corrosion fast reactors and re-processing plants, Corrosion test methods and standards.
- Non-destructive evaluation techniques for materials and components: Visual, LPT, MPT, UT, Eddy current, X-ray Radiography, Neutron, Gamma ray etc. for quality assurance and in-service inspection.
- Nuclear Fuels: Production, fabrication, properties and application of nuclear fuels (metallic fuels, ceramic fuels (oxide, mixed oxide, mixed carbide)) and heavy water. Radiation damage and post irradiation examination of core materials.

Course Outcomes:

This course enables students to classify and select engineering materials such as carbon steels, stainless steels, Cr-Mo steels, Ti-alloys, polymers, ceramics and composites based on structure–property–application relationships. It provides understanding of heat treatment, metal forming, welding metallurgy, corrosion mechanisms, metallographic characterization, non-destructive evaluation, and nuclear fuel materials, including radiation damage and post-irradiation examination.

References:

1. Introduction to Materials Science for Engineers - James Shackelford
2. Physical Metallurgy Principles & Practice - V.Raghavan
3. Introduction to Solids - L.V.Azaroff
4. Structure and Properties of Materials - Wulff Series, Wiley Eastern, New Delhi
5. Materials in Nuclear Application - C.K.Gupta
6. Nuclear Chemical Engineering - Benedict and Pigford
7. Physical Metallurgy, Reed - Hill

8. Heat treatment of steel - Avener
9. Introduction to Solid State Physics - Charles Kittel (Wiley Eastern)
10. Physical Metallurgy: Principles and Practice - V. Raghavan (Prentice Hall)
11. The Physics and Chemistry of Materials - Joel Gersten and Fiedenick Smith (Wiley, Canada)
12. Fundamentals of Materials Science and Engineering - D. Callister (Wiley, Europe)

RP: Fast Reactor Physics and Shielding (35 Lecture Hrs)

Coordinator: Shri Rajeev Ranjan Prasad
(rajeevphy@igcar.gov.in)

Course Details:

- **NUCLEAR THEORY BASICS :**
  - Properties of Nuclei: Size, shape and density of the nucleus, nuclear forces, nuclear structure, binding energy, stability of nucleus, radioactivity
  - Fission Process : Spontaneous and induced fission, liquid drop model, fission neutrons, delayed neutrons, fission gammas, fission products, fission product yield, FP mass asymmetry, formation and removal of FPs in a reactor
  - Concept of Nuclear Reactor Fission energy, fission rate and reactor power, energy balance, fissile, fertile and fissionable materials, reactor materials: fuel, coolant, structure, control and shield, fission product activity after shutdown – decay heat, types of reactors
  - Interaction of Neutrons with Matter Production of neutrons, elastic and inelastic scattering, radiative capture and their significance in reactors, production of photo neutrons, transmutation
  - Concept Cross-section Microscopic and macroscopic cross-section, mean free path, Maxwell-Boltzmann distribution and its departure, structural changes caused by neutron reactions
  - Variation of Cross-section with Energy Fast, resonance and thermal ranges, 1/v law of neutron cross-section, resonance absorption, Breit-Wigner formula, Doppler effect
  - Capture to fission ratio, Eta vs E curve, conversion and breeding concepts, Thorium utilization

- **BASIC REACTOR PHYSICS-STATIC**
  - Diffusion of Neutrons: Fick's law and its validity, steady state neutron diffusion equation, concepts of neutron flux and current, interface conditions, diffusion coefficient, diffusion length and extrapolation distance
  - Chain Reaction :Four factor formula, conceptual treatment of diffusion of one group of neutrons in non multiplying and multiplying media, infinite and effective multiplication factors, bare homogeneous reactor concepts, material and geometrical buckling, sub criticality and super criticality, critical mass, non leakage probabilities in bare homogeneous cores, neutron cycle and life time in finite reactor
  - Slowing Down Process: Neutron Slowing down, slowing down power and moderating ratio of moderators, slowing down with spatial migration, Fermi age concepts, migration length, multi zone reactors, ideas of reflectors/blankets, reflector savings, form factor

- **TIME DEPENDENCE**
  - Reactor Kinetics: Time dependent neutron diffusion equation, one group kinetic equation, role of delayed neutrons, prompt neutron life time, point kinetic model to illustrate importance of delayed neutrons, reactor period, reactivity and its units

- Core Burnup and Neutron Poisons: Burnup equations including fission products, Xenon and Samarium poisons, Xenon loads (operating and post shut down), variation of Xenon load with power and enrichment, Xenon oscillations and their control
- Reactivity Coefficients and Reactor Experiments: Temperature and void coefficients of reactivity, their relevance to reactor safety
- Techniques to control reactors, typical reactivity balance, long term burnup, fuel management, reactor control system – requirements of physics aspects, reactor shutdown mechanisms and neutron monitoring during operation and shut down
- Approach to criticality, physics measurements and calibrations/validations

- **FAST BREEDER REACTORS**
  - Introduction: Fast reactors as breeders, comparison of fast and thermal reactors, types of fast reactor, role of fast reactors in Indian nuclear power program
  - FBR Neutronics: Neutron spectrum, reaction cross-section, core characteristics, blanket characteristics, breeding potential, breeding ratio and breeding gain, doubling time, Multigroup diffusion theory methods and summary of steady state computational methods for FBR
  - Effective delayed neutron fraction and prompt neutron life time, fuel expansion and bowing, sodium void reactivity effect, Doppler reactivity effect, long term reactivity effect - in FBR
  - FBR Core Design: General features of FBR core, specific power, linear rating, burnup, fluence, requirement and choice of core materials (fuel, coolant and structural materials), test reactors, commercial fast reactors, pin diameter, core height/diameter ratio, blanket thickness.
  - Salient physics aspects of FBTR and PFBR
  - Reactor Shielding: Source of various neutron & Gamma radiation within the reactor system; Attenuation of neutrons & gamma rays; Dose rates for gamma rays for various source geometries; Buildup factors for homogeneous & multiple layer shields; Removal diffusion theory for neutron attenuation; coolant activation, heat generation. Streaming of radiation through gaps & void in the shield; description of various shielding arrangements of Indian reactors

Course Outcomes:

Students gain a comprehensive understanding of nuclear theory, neutron interactions, fission process, reactor criticality, diffusion theory, reactor kinetics and burnup behavior. The course emphasizes fast breeder reactor neutronics, reactivity feedbacks, core physics of FBTR and PFBR, and reactor shielding principles for neutron and gamma radiation attenuation.

References:

1. S. Glasstone and S. Sesonske, Nuclear Reactor Engineering, Van Nostrand, 1963.
2. S. Glasstone and M.C. Edlund, Elements of Nuclear Reactor Theory, Van Nostrand, 1952.
3. J. R. Lamarsh, Introduction to Nuclear Engineering, Addision Wesley, NY, 1960.
4. M. El-Wakil, Nuclear Power Engineering, McGraw-Hill
5. P.P. Zweifel, Reactor Physics, McGraw-Hill, 1973.
6. Weston M. Stacy, Nuclear Reactor Physics, John Wiley & Sons, Inc.
7. A.E. Walter & A.B. Reynolds, Fast Breeder Reactors, Pergamon Press.

HP: Health Physics & Radiological Safety (25 Lecture Hrs)

Coordinator: Dr. S. Chandrasekaran
(schand@igcar.gov.in)

Course Details:

- **Introduction**

Radiation sources: Natural and Induced radioactive sources, units of radioactivity, half-life and decay constant, specific activity.

Basic interaction mechanism of a) alpha b) Beta c) Gamma/X-rays d) Neutrons with matter. Definition of various dosimetric terms (exposure, absorbed/equivalent/effective dose, concept of radiation/tissue weighting factors and their importance (SI units & new units). Concepts of Exposure measurement: Free air and Air wall chambers, Exposure-dose relationship, Bragg-Gray principle.

- **Biological effects of Radiation**

Human body: Cells, tissues and organs, structure of cell, cellular effects. Factors, which influence the damage of cell. Interaction of radiation with biological matter. Radiation effects: stochastic and deterministic. Acute and delayed effects. Types of exposure (natural, occupational, medical and public).

- **Radiation Protection and Regulations**

Importance of radiation protection program in DAE, Atomic Energy act, National and International regulatory bodies, their role and responsibilities., Radiation Protection Rules, Dose limits stipulated by these bodies. Dose limits observed in India.

Radiation protection philosophy, Principles of radiation protection, concept of ALI & DAC (with suitable problems). Fundamentals of ICRP respiratory model, entry through ingestion, GI track model.

Principles of radiation detection and monitoring: Basic operating principles of a) Gas b) Scintillation (including thermo luminescence detectors) and c) Semiconductors detectors.

Type of Radiation monitors/Radioactivity measurement methods adopted for radiation protection.

- **Radiation protection and measurement (External and Internal)**

Control of external exposures (with problems in each case). Buildup concept, shielding from alpha, beta, gamma and neutron sources. Shielding from mixed sources.

Routes of intake of radioactive material,

Radiotoxicity and classification of laboratories, design of laboratory for radioactive work, Radioactive waste classification and management. Personal monitoring, area-monitoring, air monitoring. Bioassay, whole body counting techniques. Use of personal dosimeters (TLDs, pocket dosimeters)

- **Radiation Protection procedures**

Procedures followed in radiation work places, work permits, zoning concept, contamination control methods, and rubber areas, spill pack (gloves + absorbing paper), Decontamination techniques. Precautions during radioactive source storage and handling, safety during transportation. Nature of duties and responsibilities of Radiation Safety Officer/Health Physicist.

- **Nuclear Accidents, Emergency Preparedness and Management**

  Reasons for accidents, classifications of accidents, International Nuclear Events Scale. Types of emergency, emergency preparedness.

- **Radiological aspects and Environmental Impact of FBRs**

  Radiological aspects of Fuel Cycle Facilities

- **Industrial Safety Aspects**

  Introduction to Industrial Safety (accident prevention technique, Job safety analysis, control measures), Factories Act, 1948 & Atomic Energy Factories Rules, 1996, industrial safety aspects (Physical and Chemical Hazards),Industrial safety aspects (safety in Machineries, hand tools & Material handling equipments, personal protective equipments, etc)Construction safety (includes Electrical Safety & Work Permit System)

Course Outcomes:

This course develops competence in radiation sources, interaction of radiation with matter and biological systems, dosimetric quantities and exposure measurement techniques. It covers radiation protection philosophy, regulatory frameworks, monitoring and shielding methods, radioactive waste management, emergency preparedness, and industrial safety aspects relevant to nuclear facilities.

References:

1. Introduction to Health Physics – Herman Cember
2. Introduction to Radiation Protection – Alan Martin
3. IAEA Regional Basic Professional Training Course on Radiation Protection (Course jointly organized by BARC and IAEA), October 26-December 18, 1998
4. Nuclear Radiation Detection - W.J. Price
5. Radiation Detection and Measurement - G.F. Knoll
6. Biological Effects of Radiation – J.E. Coggle
7. Nuclear Radiation Detectors by S.S. Kapoor and V.S. Ramamurthy (Publication: New Delhi, Wiley Eastern Ltd, 1986)
8. Atoms, Radiation and Radiation Protection by James E. Turner 1986
9. Problems and solutions in Radiation Protection by James E. Turner, 1988
10. Guide Lines for Hazard Evaluation Procedures – American Institute of Chemical Engineers
11. Risk Analysis in the Process Industries: The Institute of Chemical Engineers, England.
12. Loss Prevention in The Process Industries: Hazard Identification, Assessment and Control; Vol-1, 1996 2 Edition, Frank P Lees.

NR: Nuclear Reactors (50 Lecture Hrs)

Coordinator: Shri D.Nagasivayya (dnsiva@igcar.gov.in)

Course Details:

- **Mechanical Aspects of Power Plant Engineering:**

  Basic thermal Cycle used in NPS, means of Improving cycle efficiency, Major components in thermal and Nuclear stations, Heat Balance typical calculations, Details of equipment – Steam Generators, Turbines, Condensers, Feed Water heaters, De-aerator feed pumps, condensate and other pumps: condenser cooling water system: C&I; steam pressure control, steam discharge and steam dumping features.

- **Thermal Power Reactors :**

  Layout of Nuclear Power Plant; Zoning requirements: layout of typical PHWR; description of layout in the reactor building; Special requirements for'; nuclear components regarding material selection, reliable operation with examples of pumps, valves, heat exchangers etc. operating environment (including capabilities to withstand seismic loads). Description of calandria, end shield and coolant channel (including fitting). Description of reactivity control scheme and related hardware e.g. zone control, regulating rods, absorbers, shutdown systems etc. Fuel and Fuel transfer system; Primary Heat Transport System; emergency core cooling system; Moderator system; Auxiliary System; Description of process Water, Fire Water and Ventilation system (emphasis on role played as safety support systems); Containment and associated safety systems to mitigate consequences of accidents and contain reactivity release; ultimate heat sink and heat removal paths.A brief overview of PWR, BWR and AHWR

- **Fast Power Reactors :**

  Fast Reactor Physics and Safety: Role of FBR’s, breeding ratio, doubling time, core design features - Static and Dynamic, control rod design, shielding principles, Fuel management, safety.

  Overview of FBR: FBTR and PFBR. Comparison of FBRs: Core & important design parameters, comparison of core components, major primary and secondary system components.

  Core Engineering: Description, choice of core materials, Engineering design of core, High temperature design methods.

  Heat Transport Systems: Introduction, Design of IHX, SG, sodium pump, sodium piping, Decay heat removal system.

  Instrumentation & Control: FBR instrumentation requirements, Neutronic Instrumentation and failed fuel detection methods, Reactor protection instrumentation and process instrumentation.

- **Sodium Technology (NRST)**

  - **Properties of Sodium:** Physical and chemical properties, (Hazardous nature and sodium-air, sodium-water reactions), heat transfer properties, Manufacture of sodium, Heat transfer in liquid metals, Hartman effect in liquid metals
  - **Sodium Systems – General Description:** Components of a sodium system, process, cover gas system etc.
  - **Impurities in Sodium, Purification Methods:** Impurities in sodium, purification methods, impurity monitors, (plugging indicator, on-line hydrogen, oxygen and carbon monitors)
  - **Sodium System:** Components, piping and Quality Control Materials, design aspects, tanks, valves, vapor traps and other mechanical engineering aspects, sodium centrifugal pumps, high temperature

piping for sodium, fabrication aspects, quality control

- **Sodium Pumps and flowmeter:** Electromagnetic pumps and flowmeter for sodium systems
- **Electrical Systems for Sodium Loops:** Electrical supply, heating systems, heater control, types of power supply
- **Instrumentation and Control:** Level, leak, flow and temperature monitoring, pressure measurement, control of process parameter in sodium systems, under sodium viewing.
- **System Operation Aspects:** Sodium system pre-commissioning checks, methods of checking all components, limiting conditions of operation, surveillance checks etc.
- **Sodium component cleaning, fire and safety**
- Sodium removal and sodium disposal methods, sodium fire and extinguishment methods, system and industrial safety aspects.

Course Outcomes:

Students acquire knowledge of thermal and fast nuclear reactor systems, including PHWR, PWR, BWR, AHWR, FBTR and PFBR, along with reactor components and heat transport systems. The course emphasizes sodium technology, instrumentation and control, safety systems, containment, decay heat removal, and operational aspects of nuclear power plants.

References:

1. Nuclear Power Engineering, M. EI-Wakil, Mcgraw Hill Book Co., New York.
2. Steam Power Station, G.A. Gassort.
3. Power Plant Engineering & Economics, Strosal & Vapet.
4. Central Electricity Generating Board (London), Modern Power Station Practice, Nuclear Power Generation Ed 2, Oxford, Pergamon, 1971.
5. Weisman. J. Modern Power Plant Engineering, Englewood Cliffs, Prentice Hall, 1985.
6. IAEA Directory of Nuclear Reactors, Vol. IV, Power Reactors, Vienna.
7. Fast Reactor Technology: Plant Design, J. G. Yevick, M.I.T. Press.
8. Fast Breeder Reactors, A.E. Waltor & A.B. Reynolds, Permagon Press.
9. Status of liquid metal cooled fast reactor technology, IAEA-TECDOC—1083
10. Material for Sodium Technology portion will be provided during the course.

RE: Reactor Engineering (40 Lecture Hrs)

Coordinator: Shri Sriramachandra Aithal
(aithal@igcar.gov.in)

Course Details:

- **Core design**
  - Introduction - Role of FBR, Main Characteristics of LMFBR, Sodium as coolant, Core Configuration, Definition of NSSS & BOP, Pool & Loop Type Design.
  - Fixing Size & Parameters of LMFBR - Test Reactor, Commercial & Prototype Reactor, Unit energy cost, Hot Spot temperature of Clad, Optimisation on Pin Diameter.
  - Definition of Smear Density, DPA & Burn up.
  - Fast Reactor Core – Fuel, Basic Requirements, Choice of fuel material, Candidates for Fuel, Swelling, Fabrication cost, Reprocessing, Negative Doppler coefficient, Thermal expansion, Burnup.
  - Absorber – required features, candidate materials.
  - Structural Material in Core - Requirements of Core Structural Material, Effect of Neutron Irradiation on SS, Radiation Hardening, Embrittlement, Void Swelling, Irradiation Creep, Effect of Swelling & irradiation induced creep, Efforts to reduce swelling
  - Sub-Assembly (SA) Design - Basis for Number of pins in a fuel SA, Pin spacers, Gas Plenum, Duct considerations, Volume Fraction, Assembly Length.
  - Other Subassembly design - Blanket, CSR, DSR, Reflector, Inner B_4C, Outer B_4C and Steel Shielding subassemblies.
  - Thermal Design of Fuel Pin - Thermal Analysis, Causes for fuel restructuring, Developing Analytical Model, Necessary physical parameters, Na Heat Transfer coefficient, Hot spot Analysis, Calculation of temperature distribution across fuel pin.
  - Mechanical Design of Fuel Pin - Failure Criteria for Pin, Strain Limit Approach, Cumulative Damage Fraction, Stress analysis, Cladding wastage.
  - Hydraulic Design of Core - Factors to be reviewed for Core Hydraulic Design - Hydraulic lifting force, Mixing studies, Power flattening & flow zoning, Vibration.
  - Handling of core subassemblies - Inherent problems associated with on-line fuel handling, Fresh SA Handling, Spent SA Handling.
- **Coolant circuits**
  - Selection of coolant for FBRs, thermal, transport, nuclear, chemical and other considerations. comparison between various coolants. Special characteristics of sodium. Its impact on heat transfer and structural mechanics considerations. Selection of structural materials, basis and important alloying elements
  - Main heat transport system: primary and secondary sodium system, necessity of intermediate loop. Safety Grade decay Heat removal system, Decay heat, necessity for independent system.
  - Features of major components such as intermediate heat exchangers, steam generators, sodium to air exchangers, sodium pumps, electro magnetic pumps, sodium tanks, support design for sodium components from thermo mechanical and seismic considerations, sodium valves and types

- Design criteria, Loadings to be considered, Analysis method and validation methodology
- Special characteristic of sodium piping, sodium leak, sodium fire, various types of leak detectors, continuous and discontinuous level detectors etc.
- Sodium purification loop, oxygen control, plugging indicator, cold trap, characteristics and features
- Operating experiences of fast reactors, failures and sodium leaks reported for Phenix, Monju, PFR and other fast reactors, reasons for leak and remedy.

Course Outcomes:

This course provides in-depth understanding of fast reactor core design, including fuel pin thermal, mechanical and hydraulic design, smear density, burnup, irradiation effects and subassembly design. It covers sodium coolant systems, major reactor components, design criteria, safety considerations, and operating experience of fast reactors.

References:

1. Fast Breeder Reactors - Walter, A.E. & Reynolds, A.B., PERGAMON Press.
2. Fast Reactor Technology - Plant Design - Yevick, J.G., M.I.T. Press.
3. Fundamental Aspects of Nuclear Reactor Fuel Elements - Donald R. Olander, U.S.Department of Energy, 1985.

CORE COURSES

FRE4: Reliability Engineering (20 Lecture Hrs)

Coordinators: Dr. M. Ramakrishnan
(mramki@igcar.gov.in)

Course Details:

- **Introduction: Reliability Engg. Applied to C&I Systems**

  Explain the course coverage and the general issues related to the reliability and safety of the current C&I Systems. The reliability of computer based C&I system as a function of circuit hardware, software and human errors experienced in the NPPs and research reactors.
  Terms and definitions with adequate explanation and giving examples from electrical, electronic and computer based systems.
  Quality, Reliability, Availability, Maintainability and supportability, MTBF, Failure and hazard rates, CCF, CMF, Failure Modes, FMEA, FMECA, Fault tolerance, Confidence and Risk Factors etc.

- **Reliability Maths/Statistics:**
  - Mathematical and statistical expressions required for reliability study.
  - Types of failures in electrical, electronic and computer components
  - Failure probability concept, statistical distribution models_
  - Binomial, Poisson, Exponential, Normal, Lognormal, Weibull distributions
  - Chi-square distribution and its use in confidence and risk factors
  - Baye's theorem
  - Reliability or life characteristics of hardware electronic circuit components, and comparison with the characteristics of mechanical/electro-mechanical components and computer software.
  - Bath-tub curve and explanation of different parts of the life characteristic curve, and corresponding failure distributions.
  - Derivation of exponential reliability expression_
  - R(t)=[exp-(lt)] for electronic components and systems.
  - Examples to solve

- **Fault Tolerance and Systems Reliability:**
  - Fault tolerance concept for electronic and Computer based C&I systems.
  - Circuit hardware redundancy concept to enhance system reliability, types of redundancy_
  - Series, parallel, active, passive, and voting redundancy
  - Redundancy and other fault tolerance methods for software
  - FMEA, FMECA concepts for C&I and Examples to solve
  - Concepts for the analysis of System Reliability, availability, and maintainability.
  - System reliability and availability analysis methods:
  - Boolean logic
  - Digraph, cutest-tie set method
  - Fault tree model, and consideration of CCF, CMF, software errors
  - Markov Model
  - Example from C&I system in the NPPs

- **QA/QC Concepts in Brief:**

- QA/QC Concepts in the components, systems procurement, manufacture and
- Site installation for C&I systems in the NPPs.

- **Environmental Qualification and Reliability Testing:**
    - Environmental qualification, testing of the C&I systems.
    - Effects of various environments on the electrical/ electronic components
    - Climatic Qualification tests: Temperature, Humidity
    - Special environments: EMI/EMC tests on C&I Systems, Gamma radiation/LOCA Qualification tests
    - Reliability Testing of the electronic components, equipment and C&I systems.
    - Reliability screening tests for electronic components
    - Accelerated environmental tests
    - Failure terminated and time terminated tests
    - Estimation of MTBF (q)/Failure Rate(l) of electronic components and systems using c2 distribution for confidence level.
    - Few examples to solve

- **Additional safety concepts:**
    - Defense-in-depth, fail-safe concepts in the design of C&I, and other safety critical systems in the NPPs.
    - Single failure criteria, engineered safety systems in the NPPs
    - Safety Classification and Seismic categorization of C&I Systems
    - Target reliability goals, reliability allocation to safety systems as per their safety importance in the NPPs
    - Reliability and safety aspects for the integrated C&I systems
    - (hardware, software, human errors considerations)
    - IEC, IAEA, AERB, IEEE standards relevant to C&I in the NPPs
    - Human Factors (man-machine interface) reliability, and human reliability issues in the NPPs
    - Current research topics in reliability and safety analysis such as Fuzzy Logic, Neural Network Methods

- **PSA/PRA Concepts in NPPs:**
    - Probabilistic Safety (Risk) Assessment: PSA/PRA methods or safety/ risk assessment in the NPPs.
    - Explain Event Tree
    - Fault-Tree-Fault Tree method for risk assessment in terms of core damage frequency.
    - Level-1, Level-2, Level-3 PSA studies (Brief introduction only).

- **Additional safety concepts:**
    - Defense-in-depth, fail-safe concepts in the design of C&I, and other safety critical systems in the NPPs.
    - Single failure criteria, engineered safety systems in the NPPs
    - Safety Classification and Seismic categorization of C&I Systems
    - Target reliability goals, reliability allocation to safety systems as per their safety importance in the NPPs
    - Reliability and safety aspects for the integrated C&I systems
    - (hardware, software, human errors considerations)
    - IEC, IAEA, AERB, IEEE standards relevant to C&I in the NPPs
    - Human Factors (man-machine interface) reliability, and human reliability issues in the NPPs
    - Current research topics in reliability and safety analysis such as Fuzzy Logic, Neural Network Methods,

Course Outcomes:

This course equips students with the ability to analyze reliability, availability, maintainability and safety of computer-based C&I systems in nuclear power plants. It covers statistical reliability models, fault tolerance, FMEA/FMECA, fault tree and Markov analysis, QA/QC, environmental qualification, PSA/PRA concepts, and relevant IEC, IAEA, AERB and IEEE standards, including human reliability aspects.

References:

1. Reliability Engineering for Nuclear and other High Tech Systems By Lakner and Anderson, Elsevier Applied Sci. Publ. (1985)
2. Reliability Engineering for Electronic Systems By R.H. Mayers et al, John Wiley, NY (1964)
3. Practical Electronics Reliability Engg By Jerome Klion, Van Nostrand, NY (1992)
4. Reliability and Risk Analysis By Norman J McCormick, Academic Press (1981)
5. Fault Tolerant and Fault Testable Design By Parag K. Lala, Prentice Hall, (1985)
6. Dependability of Critical Computer Systems, Vol.1&2 By F.J. Redmill, Elsevier Applied Sci. Publ. (1988)
7. An Introduction to Reliability and Maintainability Engg By Charles E. Ebeling, Tata-McGraw Hill Publ. (1997)
8. Reliability Technology By A.E. Green and Bourne, UKAEA, John-Wiley (1972)
9. IEC Standards: 880, 987, 1225, 1226 on C&I Systems
10. AEA Safety Standard/Guide G:1.3, Instrumentation & Control for the safety of Nuclear Power Plants (2002)
11. IAEA-TECDOCS: 780, 790 on Computer based C&I Systems.
12. MIL-Std-217F: US Military Handbook: Reliability Prediction of Electronic Equipment (1993)
13. Reliability of Computer and Control Systems by Viswanadham et al, North-Holland/ Elsevier Publ.(1987)
14. Software Reliability Methods, by Doron A.Peled (Bell/Lucent Labs), Springer Publisher (2001), ('Formal Methods' has been explained).
15. Handbook of Reliability Engg Ed. Igora Ushakov & R. Harrison John Wiley & Sons (1994)
16. Burn-in by Fenn Jenson Failure Models by I.B. Gertsbakh
17. System Reliability_ Concepts & Applications by K.B. Klassen (1989).

FRE5: Process Design and Control (30 Lecture Hrs)

Coordinator: Dr. K. A. Venkatesan (kavenkat@igcar.gov.in)

Course Details:

- State Variable Descriptions Introduction, The concept of state, Elementary definitions, state space representations of continuous-time and discrete-time systems, State diagrams, illustrative examples, solutions of state equation, state transition matrix, computation methods of state transition matrix, relationship between state equations and transfer functions, characteristic equations.
- Controllability and Observability: Introduction, definitions of Controllability and Observability, Controllability and Observability tests, Kalman Controllability Criteria, Principle of Duality, Controllability and Observability of discrete – time systems
- Control System Design: Introduction to state feedback, Controller design using pole placement technique, Stabilizability, LQR technique.

Course Outcomes:

This course develops understanding of state-space modeling of continuous and discrete-time systems, including state equations, state transition matrices and their relation to transfer functions. It emphasizes controllability, observability, state feedback, pole placement, stabilizability and optimal control using LQR techniques for control system design.

References:

1. John J.D'Azzo and C.H.Houpis, "Linear Control System Analysis and Design- Conventional and Modern", 2nd Ed. McGraw Hill Book Co.1986.
2. Chi-Tsong Chen, "Linear System Theory and Design", CBS College Publishing, Holt, Rinehart and Winston, 1984.
3. M.Gopal, "Modern Control System Theory", 2nd., Wiley EasternLtd.,1993.
4. Gene F. Franklin et al, "Feedback Control of Dynamic Systems", 3rdEd., Addison-Wesley Publishing Co. 1994.
5. B.Friedland, "Introduction to State-space methods"
6. K.Ogata, "Modern Control Engineering", Prentice- Hall.
7. H.Kwakarnaak, R.Sivan-"Linear Optimal Control Systems"-Wiley interscience
8. D.G.Schultz,James.L.Melsa- "State Function and linear control systems"- McGraw Hill.

FRE8 : Emergency Preparedness and Disaster Management (20 Lecture Hrs)

Coordinator: Dr. Vidya Sundararajan
(vidya@igcar.gov.in)

Course Details:

- **Emergency Preparedness**

  Bases and contents of emergency response plan by operating organization, Classification of emergencies - Emergency Standby - Personnel Emergency - Plant Emergency Site Emergency - Off-Site Emergency, Organisation for emergency response – Plant Emergency organization - Site Emergency Organisation – Off-Site Emergency Organisation., Emergency measures – Notification - assessment action during emergency - Corrective Actions - Protective Measures - Contamination Control Measures - Termination of Emergency, Assistance to affected personnel - First-aid - Decontamination - Transportation- Medical Treatment, EMERGENCY PREPAREDNESS – Training - Exercises - Review and Updating of Plans and Procedures - Emergency Equipment and Supplies

- **Disaster Management**

  - **Nuclear and Radiological Emergency/Disaster Scenarios**
    Nuclear and Radiological Emergency/Disaster Scenarios, Accidents in Nuclear Power Plants and Other Facilities in the Nuclear Fuel Cycle, 'Criticality' Accidents, Accidents during Transportation of Radioactive Materials, Accidents at Facilities using Radioactive Sources , Nuclear/Radiological Terrorism and Sabotage at Nuclear Facilities, Need for a Comprehensive National Radiation Emergency Management System , Disaster Management in India

  - **Approach to Nuclear and Radiological Emergency Management**
    Strategies for Nuclear Emergency Management, Nuclear Emergency Management, Framework, Prevention of Nuclear Emergencies, Emphasis on Prevention (Risk Reduction) and Mitigation Measures, Prevention (Risk Reduction), Mitigation Measures , Compliance with Regulatory Requirements, Nuclear Emergency Preparedness, Capacity Development , Nuclear Emergency Response, Strengthening the Framework of Nuclear Emergency, Monitoring the Implementation of Nuclear/Radiological Emergency Action Plans

  - **Mitigation of Nuclear/Radiological Emergencies**
    Mitigation Measures, Defence-in-Depth: Salient Features, Mitigation of Nuclear and Radiological Emergencies, Engineered Safety Features, Accident Management, General Mitigation Features, Engineered Safety Features (to Mitigate the Consequences of an Accident) in Nuclear Power Plants

Course Outcomes:

This course provides knowledge of nuclear and radiological emergency preparedness, including classification of emergencies, emergency response organization, protective measures, contamination control and emergency termination. It also covers disaster management strategies, mitigation measures, defence-in-depth, accident management, and national frameworks for nuclear and radiological emergency management.

FRE15: Reactor Control Engineering (30 Lecture Hrs)

Coordinator: Dr. V.L. Anuraj
(anuraj@igcar.gov.in)

Course Details:

- Physics of Reactor Control
- Reactor Kinetics – Point kinetic model, reactor response to step and ramp reactivity inputs, stable reactor period.
- Reactor as a control element: basic zero energy state space model and transfer function, feedback loop transfer functions, effect of temperature and voidage, poisoning due to xenon and samarium, fuel burn-up, reactor system stability analysis from transfer function and state space model. Manual and computer control.
- Large reactor control: Neutronically decoupled cores. Modeling techniques for large reactors-modal, nodal and quasi-static methods (introduction only) flux tilt and spatial instability.
- Typical reactor control system: BWR, PWR, PHWR, Fast Reactor, research reactor and 235MWe PHWR, FBTR and PFBR.
- Reactor operation: Approach to criticality, re-start up, operation in power range, shut down.
- Power plant control: Power plant programming. Constant T_{av} program, constant pressure program, boiler level and pressure control. PHT pressure control. Pressuriser pressure and level control. Secondary circuit and feed water control.

Course Outcomes:

This course enables students to understand reactor kinetics, reactivity control, feedback effects and reactor stability using transfer function and state-space models. It covers control systems of BWR, PWR, PHWR, fast reactors, reactor operation from approach to criticality to shutdown, and power plant control strategies.

References:

1. Nuclear reactor physics – W.M. Stacey. John Wiley and sons. 2001.
2. Nuclear reactor kinetics – Ash. M. Mcgraw Hill, Newyork, 1979.
3. Nuclear reactor kinetics and control, Weaver. L.E. American Elsevier, 1968.
4. Optimal control of nuclear reactors, Mohler.R.B. and Shen.C.N., Academic Press. 1970.

FRE16: Nuclear Instrumentation (25 Lecture Hrs)

Coordinator: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- Fundamental considerations/philosophies, requirements and scope-Reactor and Health Physics Instrumentation
- Principles of detection and types of radiation detectors: in-core and out – of –core. Consideration in reactor start-up (cold & hot) and normal operation, GM counters, Scintillators, Gamma Ion chambers
- Detector signal conditioning (Pulse, Campbell and DC modes) and generation of logarithm & period signals
- Block Schematics of Pre-amplifier, Count rate meters, Nuclear ADCs, MCA, Low-voltage and High voltage Power supplies, Scalar timers.
- Introduction to various reactor instrumentation and radiation monitors:
- Start-up, Intermediate and Power Range Instrumentation, Reactor Regulating System, Flux Mapping System, Failed Fuel Detection System, Stack Monitoring System, Area Gamma and Neutron Monitors, Contamination Monitors, GM Survey meters, Gun monitors, Neutron REM monitors, RADAS

Course Outcomes:

This course provides comprehensive knowledge of radiation detection principles, in-core and out-of-core detectors, signal conditioning and nuclear electronics. It covers reactor instrumentation systems, radiation monitors, flux mapping, failed fuel detection, and instrumentation used during reactor start-up and normal operation.

References:

1. Radiation Detection and measurement -G.F. Knoll
2. Nuclear Electronics - P.W. Nicholson
3. Selected topics in Nuclear Electronics, IAEA-TECDOC-363 (CC library Acc no: 123583)
4. Nuclear Power Reactor Instrumentation Systems Handbook, Vol: 1 J.M. Harrer, J.G. Beckerly
5. The Technology of Nuclear Reactor Safety Vol1, T.J. Thompson, J.G. Beckerly.

FRE17: Embedded System Design and Human Machine Interface (45 Lecture Hrs)

Coordinator: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- **Microprocessor Based Hardware Design**

  Overview of Microprocessors: Comparative study of Intel and Motorola family microprocessors (80186, 80486, Pentium series, 68XXX), Overview of 16-bit Micro-controllers (e.g. 80196), Overview of 8-bit Atmel Micro-controller (AT89C51), Real Time Clock, DSPs (e.g. TMS320, SHARC family) and ARM processor.
  Personal Computers: Architectures, Memory organization, Industrial PC, Embedded PC
  Industry Standard Bus Systems: ISA, PCI, VME: Mechanical, electrical, functional & procedural specifications, multi-processing, bus arbitration, plug & play
  Design Case Study: Single board computer architectures, Remote Terminal Unit, Circuit design, and logic design, application of FPGA and CPLDs, ac/ dc analysis, timing analysis, thermal, EMC and signal integrity analysis. Design accommodations for testability, reliability and maintainability. Physical design and design tools.

- **Computer Communication and Networks**

  Asynchronous & synchronous communication standards, RS232C, RS485, USB, encoding (NRZI, Manchester), Modems, SDLC, Local area networks, Ethernet, Token passing principles, TCP/ IP, Fibre optic communications for LANs, wireless LANs (WAP, Blue tooth), Industrial networks, Real-time issues in networking, Networking hardware (cables, hub, switch, routers etc.);Concept of Fieldbus, fieldbus standards, Industrial networks and Protocols.

- **Fault Tolerant and Distributed Architectures**

  Principles of fault tolerance, Hot- standby and Triple Modular Redundant (TMR) configurations, software implemented fault tolerance, reliability, and availability and safety issues.
  Principles of distributed systems, architectures, Distributed control systems, Impact of Internet technology, Web enabled devices.

- **Programmable Logic Controller Design**

  Basic PLC architecture, PLC Programming Languages, Typical PLC Specifications, Redundant PLC architectures, Relevant communication protocol and standards, PLCs for package systems.

Course Outcomes:

This course develops competence in microprocessor-based hardware design, embedded systems, industrial communication networks and distributed architectures. It emphasizes fault-tolerant designs, PLC systems, real-time networking, human–machine interfaces, and reliability considerations for industrial and nuclear applications.

References:

1. Microprocessor and interfacing: D. V. Hall – McGraw Hill
2. The Advanced Intel Microprocessors: 80286, 80386, 80486: Barry. B. Brey, - McGraw Hill
3. Microprocessor, Micro-controller and DSP Handbooks: Motorola, Intel, Texas Instruments, Analog Devices

4. Hardware Bible: W.L Rosch- Tech Media
5. VME Bus specifications: IEEE 1014- 1987
6. Embedded System design – A Unified hardware/ software introduction: Frank Vahid / Tony Givargis – John Wiley and sons
7. Computer networks: A.S. Tanenbaum, Prentice Hall
8. Internetworking with TCP/ IP: Vol I to III: D.E.Comer, Prentice Hall
9. Complete guide to networking: P. Norton & Kearns – Tech Media
10. Wireless communication & networks: W. Stallings – Pearson education
11. Fault-tolerant computing – Theory & Techniques: D.K. Pradhan (Ed), Vol I & II – Prentice Hall
12. The theory and practice of reliable system design: D.P. Siewiorek& R.S. Swarz, Digital press
13. Modern Operating Systems: Andrew S Tanenbaum, Prentice Hall
14. Distributed Operating systems: A .S. Tanenbaum – Pearson education
15. Windows NT device driver development: P.G. Viscarola & W. Mason – Tech Media
16. Real-time systems: Jane W.S. Liu – Pearson education Hill.
17. IntellutionIfix documentation
18. NPC Guidelines for development of soft consoles

FRE18: Process Instrumentation (45 Lecture Hrs)

Coordinator: Dr. N. M. Meenachi
(meenachi@igcar.gov.in)

Course Details:

- Design, selection, typical specifications, calibration standards, installation, testability and diagnostics of measuring instruments of following process variables:
- Flow: Differential pressure flow elements: Orifices, venturies, flow nozzles, pitot tube, annubar, elbow flowmeter. Different standard pressure taps for orifices, sizing calculations, straight length requirements. Applicable codes for design of Orifices , venturies and flow nozzles. Orifice flanges, Jackscrews, carrier rings, flow straighteners, square root extractors, flow totalisers. Variable Area Flowmeters- Glass tube rotameters; Armoured rotameters; Bypass rotameters; Density correction factors. Magnetic, Turbine, vortex flowmeter; Ultrasonic flowmeters- transit time, Doppler type, Clamp on type ultrasonic flowmeters, Coriolis and thermal mass flowmeters, air velocity meters. Applications and limitations of various flowmeters. Two phase flow measurements.
- Temperature: Thermocouples- Types of thermocouples, ranges, sensitivity and their limits of error and applications, mineral insulated thermocouples, types of hot junctions- grounded, ungrounded and exposed junction, thermocouple extension and compensating cables, high temperature thermocouples, cold junction compensation techniques. Applicable standards. RTDs- Wire wound and thin film RTDs, limits of error, self heating error, matched pair of RTDs. Applicable standards for RTD. Thermistors -performance and applications. Thermowell - Design considerations, Applicable design code for thermowell, thermowell installation aspects. Surface temperature measurement techniques.
- Temperature transmitters- Head mounted temperature transmitters, isolated temperature transmitters, Smart temperature transmitters. Radiation thermometry- Optical pyrometer, total radiation pyrometer, two colour pyrometer, factors affecting the performance of radiation pyrometers.
- Pressure: Manometers-U tube, well and inclined manometers, pressure gauges, hydraulic and pneumatic dead weight testers- ranges and factors affecting the performance of dead weight testers. Pressure Transducers and transmitters- strain gauge, capacitance, LVDT, piezo-resistance type and piezoelectric type pressure transducers, transmitters with remote diaphragm seal, high temperature pressure transducers, Smart pressure and differential pressure transmitters. Vacuum measurement- Pirani and thermocouple gauges, cold cathode and hot cathode ionization gauge, Mcleod gauge.
- Level: Hydrostatic pressure and differential pressure methods, wet legs- cold reference leg and hot reference leg, condensing pots, density compensation in boiler level measurement, zero elevation and zero suppression. Gauge glass, Purge system, capacitance probes, displacer, ultrasonic, nucleonic, hydra step level gauge and radar level gauge. Level switches- conductivity, capacitance, ultrasonic, displacer, float type.
- Analytical Instrumentation: Conductivity, pH, ORP , Turbidity dissolved oxygen, silica and sodium Measurement. Other Measurements: Moisture, Relative humidity; viscosity and density measurement Turbovisory Instrumentation: Measurement of speed, vibration, differential expansion, overall expansion, eccentricity, Governor valve position, CIES valve position, Speeder-gear & load limiting gear position
- Sodium Instrumentation: Properties of sodium-special requirement of sodium Instrumentation-sodium flow measurement- Magnetic flowmeter, Eddy current flowmeter sodium level measurement-continuous- discrete-resistance type-mutual inductance type- Sodium Leak Detection-spark plug type & wire type leak detection-Sodium aerosol detection - Mutual Induction type leak detectors - Steam Generator Leak Detection systems-Hydrogen in sodium detection- Nickel diffuser based detection-Electrochemical meter based detection-Hydrogen in cover gas (argon) detection- Failed fuel detection system-Gammatography etc.,

- Signal Conditioning Circuits: Operational amplifiers-instrumentation amplifiers-signal linearization techniques, isolation amplifiers-two port-three port isolation.
- Control valves: Valve types, construction and applications, Valve sizing calculations, Applicable standard for sizing calculations, Control valve rangeability, Valve characteristics-inherent and installed, selection of valve characteristics, Cavitation and flashing in control valves, Valve capacity testing, Valve actuators- pneumatic, hydraulic and electric, selection of actuator, Typical specifications for control valve, Smart valves, valve positioner, I/P converter, P/I converter, volume boosters, air lock relays, Solenoid valves, Pressure regulating valves, Installation aspects of control valves, Quality of air for pneumatic valves.
- Instrument Impulse lines and instrument fittings: Tubes- materials and sizes, tube fittings- materials, types of fittings, instrument isolation valves, guidelines for routing of impulse lines, considerations for impulse line response time. Applicable standards for tubes and fittings.
- P & I Diagrams, loop and hook up diagrams: P &ID symbols, Applicable ISA standard for P &ID symbols, typical loop diagrams, typical instrument hook up diagrams.
- Control and Instrumentation Power Supplies: Class I, II, III, IV power supplies, Centralized 24V/48V DC power supply, Linear and switching mode power supplies, Fault Tolerant Dual redundancy power supplies, distributed power supplies, quality of power supply, Isolation transformer, grounding/earthing aspects in C & I systems.
- Reliability principles, Fail safe design principles, Diversity, active and passive redundancy, availability, maintainability, MTBF, MTTR, preventive-predictive-proactive-corrective maintenance-spares inventory control principles, Condition Monitoring etc.

Course Outcomes:

This course provides detailed understanding of design, selection, calibration and application of instruments for flow, temperature, pressure, level and analytical measurements. It also covers sodium instrumentation, signal conditioning, control valves, P&ID documentation, power supplies, and reliability and fail-safe principles in C&I systems.

References:

1. Principles & practice of flow meter Engineering by L. K. Spink. The Foxboro Company.
2. Fluid Meters. ASME publication
3.Manual on the use of thermocouples in Temperature Measurements (ASME Publication by subcommittee 4)
4. Measurement Systems: Application and Design, Ernest O Doeblin
5. Process Control Systems: Application, Design and Tuning, F. G. Shinskey, Mcgraw Hill.
6. Applied Instrumentation in the Process Industries, Volume I & II, Edited by W.G. Andrew.
7. Process Control Engineering, M. Polke
8. ISA Handbook of Control Valves, Editor-in-Chief J. W. Hutchison
9. British Standard Code of practice for Instrumentation in Process Control Systems: installation design and practice (BS 6739)
10. Handbook on Applied Instrumentation: Edited by D.M. Considine and S.D. Ross, Mcgraw Hill
11. Process Instruments and Control Handbook: Edited by D. M. Considine, Mcgraw Hill
12. Instrument Engineer’s Handbook, Part I & II: Edited by Bela G Liptak, Chilton Book Company
13. Instrumentation in the Processing Industries Edited by Bela G Liptak, Chilton Book Company
14. IEC standard 61131.3 - PLC Programming Languages
15. Human Factors in Control Room Design - EPRI NP 1118 / EPRI NP 3659
16. NUREG-700 Guidelines for Control Room Design Reviews, U.S. Nuclear Regulatory Commission
17. Eight Open Networks and Industrial Ethernet, (www.industrialethernet.com)
18. Basics of Field bus, Rosemount Inc. (www.rosemount.com)
19. MIL-STD-1553B Standard

ELECTIVE COURSES

FRE9: Plant Control (25 Lecture Hrs)

Coordinator: Shri M.S. Kodeeswaran (kodi@igcar.gov.in)

Course Details:

- Control Physics: Review of Reactor Kinetics - neutron power - prompt and delayed neutrons - Criticality – Reactivity Feedbacks - reactivity coefficients Sodium void coefficients;
- Reactor Control Concepts: Start-up - Operation at steady power - shutdown criteria - design considerations - reactivity disturbances and transients.
- Reactivity control devices - reactivity insertion rates – principles. Calibration of control rods.
- Plant Dynamics and Overall Control: Reactor Physics and engineering experiments
- Transient analysis concept - Routine Operating transients - Accidents such as LOCA, LOFA, reactivity excursions etc
- Thermal balance and reactivity balance calculations

Course Outcomes:

This course enables students to understand reactor control physics, reactivity feedback mechanisms and sodium void effects, and their role in safe plant operation. It develops capability to analyze reactor start-up, steady-state operation, shutdown criteria, plant dynamics, transient behavior and accident scenarios, including thermal and reactivity balance calculations.

FRE10: Turbine Generator Fundamentals (25 Lecture Hrs)

Coordinator: Shri M.S. Koteeswaran
(kodi@igcar.gov.in)

Course Details:

- Principles of steam turbine cycle, steam turbines, impulse and reaction turbines, Rankine cycle, velocity diagram for impulse / reaction turbine, state point locus or condition line for multistage turbine, reheat factor, Willan's line variation of stage pressure with load, heat rate, thermal efficiency, peak load, base load, spinning reserve and capacity factor.
- Turbine parts, construction of nozzle, turbine blades, turbine rotor, turbine casing, cylinder supports.
- General design aspects, output of a steam turbine, effect of higher steam inlet pressure, effect of high inlet steam temperature, effect of the size of the turbine, effect of back pressure on the economy of a turbine, effect of reheat, effect of feed water regenerating cycle, double cylinder construction speed of a turbine.
- Nuclear turbine, erosion of blades, methods of reducing moisture content, moisture removal within the turbine, external moisture separator, re-heater, protection of blades against erosions, over speeding of turbine.
- Lubrication of bearings, turbine oil system, theory of lubrication of turbine bearings, viscosity, oiliness, boundary lubrication, film lubrication, the journal bearing, hydro dynamic lubrication, hydrostatic lubrication, properties of oil, additives, treatment of oil.
- Governor theory, basic methods of governing, throttle governing, nozzle governing, difference between governor and fly wheel, types of governors, centrifugal governor, effect of friction, speed droop, speed regulation for machines operating, inertia governor, electric governor, new governing systems used in the latest NPPs.
- Turbovisory instruments, purpose of turbovisory instruments, location of Turbovisory instruments, differential expansion indicator, eccentricity recorder, turbine pedestal movement indicator, speed indicator and recorder, vibration indicator.
- Turbine commissioning, pre-start commissioning, lubricating oil system, checking tightness of vacuum system, flushing the condensate, feed water and other piping of the various sub-systems, turbine supervisory instruments, governor systems, main steam line blow out, Vacuum pulling, starting a new turbine for the first time.
- Pre-heating of turbine, cold start and hot start, heating process, heating rates, differential expansion of cylinder and rotor, effect of flanged horizontal joint, flange bolts, conditions in a standing hot turbine, turbine shaft turning gear, thermal expansion during warming up.
- Operation of turbine, start-up procedure, on-load operation, routine tests, turbine shutdown procedure.
- Turbine troubles, shaft vibration, disc vibration, blade vibration, internal defects of material, expansion of steam piping, corrosion of blades and diaphragms, turbine blade deposits.
- Protection and safety devices, turbine regulating system, turbine protective system, protections on boiler feed pumps, H.P. heaters and L.P. heaters
- Inspection and overhauling, lifting the cover, inspection of diaphragms, checking the clearances, inspection of rotor, Inspection of shafts, inspection of steam valves.
- Condensers, design of condenser, effect of changes in cooling water temp. in condenser operation, effect of varying cooling water flow on condenser back pressure, air leakage, water leakage, maintenance of condensers, condenser as a deaerator, back washing of condenser, Hoggers and methods of vacuum creation, replacement of Hoggers with vacuum pumps, reasons for this replacement and their advantages.
- Regenerative feed heating, selection of feed heating system, components of feed water system, effectiveness of feed water heater, deaerating contact heaters, deaerators, closed heaters, cascading of feed water heater drains, venting of feed water heaters, performance of feed heaters.
- Boiler feed pumps, condensate extraction pumps and controls, Boiler feed pump and controls, Boiler feed pump recirculation and up warm-up lines, Net Positive Suction Head (NPSH) for a pump, boiler feed pump

NPSH.

- Chemical control, design intent of a system chemical control, review of basis and material of construction, co-ordinated phosphate pH control, all volatile or zero solid treatment, mixed treatment, Oxygen scavenging, ferrous sulphate injection for prevention of condenser tube corrosion.
- Generator and auxiliaries, stator cooling water system, hydrogen cooling system, seal oil system.

Course Outcomes:

This course provides comprehensive knowledge of steam turbine cycles, turbine–generator construction, governing systems and lubrication practices used in nuclear power plants. It equips students to understand turbine operation, commissioning, protection systems, condenser and feed heating systems, and diagnosis of turbine-related operational problems.

FRE11: Mechanical and Electrical Equipment (25 Lecture Hrs)

Coordinator: Shri M.S. Koteeswaran
(kodi@igcar.gov.in)

Course Details:

- Bearings and Lubrication, Types and identification of bearings - Illustration of different types of bearings - Selection of bearings - Lubrication methods - Types of lubricants - Lubricant properties - Bearings and lubrication methods used in: - Turbine – Primary & Secondary sodium Pumps - Boiler feed pump Bearing mounting in motors (Horizontal and vertical) - Operating care for bearings - Causes of bearing failure.
- Seals, Types of static and dynamic seal. Gland packing - Mechanical seal - O ring – etc. Inspection of mechanical seal - Causes of failure of mechanical seals - Operating care for all the seals - Importance of seals in nuclear power plant operation.
- Power Transmission, Types of couplings and belts - Application of various couplings like tyre coupling, love joy coupling, steel flux coupling, bush and pin sliding disc, sliding block, flange muff and coupling. - Types of misalignment - Effects of misalignment on equipments.
- Pumps, Types of pumps - Centrifugal, rotary and reciprocating pumps – Pumps used in Sodium system- Construction details of pumps - Types of casing - Types of impeller - Effects of radial thrust and axial thrust - Methods of balancing of radial thrust and axial thrust - Operation of centrifugal pump, external gear pump, internal gear pump, screw pump, radial piston pump - Head - Flow characteristics of centrifugal pump - System head characteristics - Power characteristics of centrifugal pump - Effect of drooping head characteristic - Cavitations, aeration and Net Positive Suction Head (NPSH) - Series and parallel operation of centrifugal pump - Practical operation of centrifugal pump and rotary pump - Effect of direction of rotation - Primary heat transport pump - disassembly and assembly - alignment procedure - lift adjustment - Canned rotor pump details, operation and testing – Trouble shooting procedures. Vacuum pumps - Types of vacuum pumps.
- Electromagnetic Pumps – types of EM pumps – construction- characteristics- protections for EM pump- Operation of EM pumps.
- Valves and Actuators, Types of valves - gate valve - globe valve - check valve - relief valve and safety valve - butterfly valve - diaphragm valve -bellow seal valve Application of the above valves - Construction detail of valves Gland packing - Live loading - Testing of valves - Types of valve actuator - Features of actuators - Hopkinson actuator -Limitorque actuator -Rotork actuator -piston type actuator - diaphragm type actuator. Operation of the above actuators - Test procedures for valves actuators.
- Sodium system valves – bellow seal valves – frozen seal valves
- Hydraulics, Circuits and control - Hardware in hydraulic circuits -tube -pipe -fittings and connectors :- flared fitting, swagelok fitting, quick disconnect coupling.-hoses - Specifications of hardware parts - Operation and maintenance problems - Hydraulic controls, types and application of - hydraulic cylinder – pressure regulating valves - directional valves - sequence valve -decelerating valves - flow control valves - Effect of pressure and flow of hydraulic oil on actuators.
- Compressors, Types of compressors - Constructional details of - reciprocating compressor - sliding vane compressor. Blowers- Types of Blowers.
- Chillers. Types of Chillers , refrigerants, refrigeration cycles, Air handling units
- Filters, Types of filters & specifications, HEFA filters, testing of HEFA filters
- Heat Exchangers, Types of Heat Exchangers - Types of tube and tube sheet connections - General details of heat exchangers. Types of maintenance
- Piping and Tubing, and pipe fitting.
- Vibration and measurements, Causes of vibration, characteristics of vibration, significance of displacement, velocity, acceleration, phase and frequency. Single plane balancing. Vibration measurement devices.

- **Power Systems and Electrical Equipment**

  - **Part – I: Power Systems**

Grid characteristics, Interaction of NPP with grid, Power system analysis and representation, Voltage and frequency control, Synchronous machines, synchronizing and load shedding, Main output and station service systems, Line, transformer and generator protections, Short circuit calculations, Power systems components

single line diagrams, concept of real and reactive power flows, voltage and frequency relations to real and reactive power, AC and DC transmission systems, Automatic voltage and frequency control, Definitions of related plant factors, synchronous machine theory, isolated and parallel operation, Automatic voltage regulator, Stability of alternators, steady state & transient stability, abnormal operating conditions, Excitation systems, loss of excitation, loss of synchronism, current unbalance, switchyard concepts, Station service and unit transformer arrangements, Classes of power supplies, standby systems, Automatic and emergency transfer schemes, Transformer, switchgear and protective relaying concepts, specific relaying for generators, motors, transformers, buses and transmission lines.

  - **Part – II Electrical Equipment**

Electrical control components and circuit checks. (415V / 3.3kV / 6.6KV), Principles of electrical control, control circuit components like relays, contactors, switches, fuses, control transformers, indicating lights, terminal blocks, control cables, Reading of electrical drawings, Local and remote controls, interlocks, push buttons, types of hand switches, forward / reverse controls, resetting meaning of logic, auto and standby modes, motor control centres (MCCs), MCC types, parts, construction, Pump, valve, crane, diesel generator controls, synchronizing controls, circuit breaker controls,

Various types of starters and controls (D-O-L), Star- Delta (manual and automatic)

- Electrical test equipment in commissioning checks.
- Use of test equipment in commissioning including - Meggers, Motor Rotation Testers - Phase Sequence Indicators - Transformer Turns Ratio Testers - Tachometers - Tong testers – Multimeters, Resistance bridges - Stroboscopes - Oscilloscopes – Harmonic Analyzers
- Commissioning tests on motors, generators, transformers, valve actuators, switchgear, protective relays, batteries and chargers
- Motors, Identification of motor leads - Measurement of insulation and winding resistance - Measurement of no load current, speed, bearing checks -Magnetic balance tests - Measurement of power factor
- Transformers, Polarity checks - Measurement of turns ratio, vector group - Insulation checks - No load and short circuit tests - Measurement of magnetizing current - Measurement of %impedance - Measurement of dielectric strength of insulating oil - New types of transformers – dry type transformers - On line tap changers
- Generators, Measurement of insulation and winding resistance - Starting, stopping, synchronizing, loading and unloading - Phase sequence tests, Excitation control.
- Switchgear, Measurement of contact resistance - Measurement of closing and tripping time - Measurement of contact pressures - Study of link mechanisms - Study of stored energy features.
- Valve actuators, Limit and torque switches - Valve position indicators – Types of actuators.
- Protective relays, Calibration of relays - Use of primary and secondary injection tests - Testing of time over current, thermal overload and directional relays - Study of relay test sets - Multiamp, Gyro, English Electric Makes - Solid state protective relays and their use in NPPs – Latest methods in relay testing using micro-processors.
- Batteries, Parts of lead acid cells - Measurement of specific gravity, voltage - Charging and discharging of cells - Study of charging circuits, Nickel cadmium batteries.
- High Voltage Equipment, High voltage equipment and electrical layout study of high voltage equipment like - Current transformers - Potential transformers - Disconnect

switches - Capacitor voltage transformers - Line traps - Air blast circuit breakers, SF_6 ,Circuit breakers.

- Lightning arresters.
- Switchyard layout, indoor and outdoor switchyards, problems associated with costal sites - corrosion, salt deposition, line washing.
- Uninterrupted Power Supplies (UPS), Control UPS and Power UPS, SCADA.

Course Outcomes:

This course develops in-depth understanding of mechanical systems, pumps, valves, bearings, seals, hydraulic systems and sodium equipment, along with their operation and maintenance in NPPs. It also provides strong grounding in power systems, electrical equipment, protection schemes, commissioning tests and fault diagnostics essential for plant reliability.

FRE12: Maintenance Engineering (25 Lecture Hrs)

Coordinator: Shri M.S. Koteeswaran (kodi@igcar.gov.in)

Course Details:

- Overview of maintenance in NPPs, Challenges in NPP maintenance, Maintenance economics.
- Reliability engineering and maintenability, Definition of reliability, bathtub curve, reliability prediction for complex plant, reliability for series and parallel arrangement, Maintainability, Availability, mean time to failure, (MTTF) mean time to repair (MTTR), means adopted to improve reliability in NPP.
- Maintenance policies, Different types of maintenance policies, fixed time maintenance, condition based maintenance, opportunity based maintenance, operation to failure maintenance, design out maintenance. Application and relative advantages and disadvantages of the policies.
- Maintenance planning, maintenance decision making, maintenance planning, manrem budgeting, determination of maintenance plan, classification and identification of equipment, equipment histories, selection of maintenance policy, preventive maintenance program.
- Spare parts management and inventory control, Requirement of the spare parts management. Economic order quality. Safety stock and when to order. Special condition for storage of sensitive spares, shelf life management.
- Condition based maintenance, Requirement, relative advantages and disadvantages, condition monitoring categories -on load and off load monitoring. Types of monitoring techniques i.e. lubricant monitoring techniques, wear debris analysis and malfunctions that can be detected by lubricant monitoring. Thermal monitoring, types of thermal monitoring, and parameters that can be detected by thermal monitoring.
- Vibration monitoring, basic characteristics, analysis, vibration meter construction, factors contributing to vibration monitoring.

Course Outcomes:

This course equips students with knowledge of maintenance strategies, reliability and maintainability concepts, and their application in nuclear power plants. It emphasizes maintenance planning, spare parts management, condition-based maintenance techniques, including vibration, thermal and lubricant monitoring for improved plant availability.

FRE13: Regulatory Framework for NPPs (25 Lecture Hrs)

Coordinator: Dr. S. Chandrasekar(schand@igcar.gov.in)

Course Details:

- The Atomic Energy Act 1962 and the Factories Act 1948, Salient features of the Act covering the major provisions and including brief title, scope of application, appropriate government, ownership, processing and usage of radioactive materials, authorisation for power generation and storage of certain chemicals, regulating and enforcing bodies under the Act. Salient features of the Factories Act 1948 with particular emphasis on safety and welfare provisions, inspection of factories and returns needed to be filed. Salient features of the Atomic Energy (Factories) Rules 1996 and authorisation for safe disposal of radioactive waste.
- The Atomic Energy Regulatory Board (AERB), Evolution of AERB. Statutory status, role, powers and activities of AERB. Approach to safety as defence in depth. Authorisation process - site approval, construction authorisation, commissioning authorisation, operating authorisation, life extension of NPPs, decommissioning authorisation. Regulatory inspection. Safety assessment. Role and powers of SORC and SARCOP. Staffing, training, qualification and licensing. Simulator training and human error reduction. Design review for plant modifications. Major guidelines for NPP O&M. Technical specifications. Licensing practices. Independence of the regulatory body. Periodic review of NPPs. Advisory committees of AERB. Instances requiring notification and clearances.
- Electricity Act 2003 and the Boiler Act, Salient features of the act covering the major provisions and including brief title, scope of application, appropriate government, regulation and inspection of electricity generating utilities. Training and authorisation of certain personnel.
- Environmental Protection Legislation, Introductory features of covering highlights and permissions needed by NPPs under the following acts:
- The Environmental Protection Act 1986
- The Air (Prevention and Control of Pollution) Act 1981
- The Water (Prevention and Control of Pollution) Act 1974

Course Outcomes:

This course enables students to understand the legal, regulatory and safety framework governing nuclear power plants in India, including the Atomic Energy Act, AERB regulations and environmental legislation. It develops awareness of licensing processes, regulatory inspections, safety assessment, compliance requirements and environmental clearances for NPP operation.

FRE14: Practicals (6 Weeks)

Coordinator: Shri M.S. Koteeswaran
(kodi@igcar.gov.in)

- **Turbine and Generator**
  - Class room training on Generation Plant, Steam water system, Turbo- generator

- **Simulator and Fuel Handling**
  - Class room and Field Training on Fuel Handling
  - Field Training on PFBR Simulator

- **Operations**
  - **Class room Training**
    - Reactor System: Reactor Assembly, Reactor Core, Control Rod Drive Mechanisms, Emergency Core Cooling Systems
    - Sodium system: Primary Sodium System, Secondary Sodium System, Sodium Purification System, Cover Gas System, Steam Generator Leak Detection System, Sodium Instrumentation
    - Control and Electrical system, Neutronic Instrumentation, Reactor Protection System, CDPS, Power Supply Systems
    - Radiation protection

  - **Field training**
    - Reactor Operation
    - Maintenance Activities
    - Technical Service Activities
    - Quality assurance & Industrial safety

TSOs will be asked present a project report and walk-through test on the above modules.

DETAILED COURSE STRUCTURE

Foundation Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	MM	Materials and Metallurgy	25	1
2.	RP	Fast Reactor Physics & Shielding	35	2
3.	HP	Health Physics and Radiological Safety	25(15 T+10 L)	1
4.	NR	Nuclear Reactors	50	3
5.	RE	Reactor Engineering	40	2
FOUNDATION TOTAL			**175**	**9**

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	FRE1	Code Design for pressure vessel & piping	30	2
2.	FRE2	Heat Transfer and Computational Fluid Dynamics	30	2
3.	FRE3	Advanced Mass Transfer	30	2
4.	FRE4	Reliability Engineering	20	1
5.	FRE5	Process Design and Control	30	2
6.	FRE6	Vibration Engineering and Condition Monitoring	20	1
7.	FRE7	Seismic Design of Nuclear Reactors and Facilities	30	2
8.	FRE8	Emergency Preparedness and Disaster Management	20	1
CORE TOTAL			**210**	**13**

Electives (any four)					
Sr. No	**Course Code**	**Subject Title**	**Hours**		**Credits**
			(T)	**(L)**	
1.	FRE9	Plant Control	25	-	1
2.	FRE10	Turbine Generator Fundamentals	25	-	1
3.	FRE11	Mechanical and Electrical Equipments	25	-	1
4.	FRE12	Maintenance Engineering	25	-	1
5.	FRE13	Regulatory Framework for NPPs	25	-	1
6.	FRE14	Practicals	6 Weeks	-	12
ELECTIVES TOTAL			**125**	**-**	**17**

FOUNDATION COURSES COORDINATOR

Course	Coordinators	Contact
MM: Materials and Metallurgy	Dr. Vani Shankar	21147/22805,vani@igcar.gov.in
RP: Fast Reactor Physics and Shielding	Shri Rajeev Ranjan Prasad	22737,rajeevphy@igcar.gov.in
HP: Health Physics and Radiological Safety	Dr. S. Chandrasekaran	23556.schand@igcar.gov.in
NR: Nuclear Reactors	Shri D.Nagasivayya	21232,dnsiva@igcar.gov.in
RE: Reactor Engineering	Shri Sriramachandra Aithal	22468/22605,saithal@igcar.gov.in

CORE COURSES COORDINATOR

Course	Coordinators	Contact
FRE1: Code Design for Pressure Vessel & Piping	Shri. S. D. Sajish	22795/22452,sajish@igcar.gov.in
FRE2: Heat Transfer and Computational Fluid Dynamics	Shri U.Parthasarathy	22775,ups@igcar.gov.in
FRE3: Advanced Mass Transfer	Shri Sourabh Agarwal	22736,sourabh@igcar.gov.in
FRE4: Reliability Engineering	Dr. M. Ramakrishnan	22611/22254,mramki@igcar.gov.in
FRE5: Process Design and Control	Dr. K. A. Venkatesan	22631/26857, kavenkat@igcar.gov.in
FRE6: Vibration Engineering and Condition Monitoring	Shri S. Chandramouli	21046/mouli@igcar.gov.in
FRE7: Seismic Design of Nuclear Reactors and Facilities	Shri S. D. Sajish	22795/22452,sajish@igcar.gov.in
FRE8: Emergency Preparedness and Disaster Management	Dr.Vidya Sundararajan	22474/22454, vidya@igcar.gov.in

ELECTIVES COURSES COORDINATOR

Course	Coordinators	Contact
FRE9:Plant Control	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE10:Turbine Generator Fundamentals	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE11:Mechanical and Electrical Equipments	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE12:Maintenance Engineering	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in
FRE13: Regulatory Framework for NPPs	Dr.S. Chandrasekaran	23556, schand@igcar.gov.in
FRE14:Practicals	Shri M.S. Koteeswaran	26224/26319,kodi@igcar.gov.in

FOUNDATION COURSES

MM: Materials and Metallurgy (25 Lecture Hrs)

Coordinator: Dr. Vani Shankar
(vani@igcar.gov.in)

Course Details:

- Classification of Materials: Structure, Ferrous and non-Ferrous metals, Polymers, Ceramics, Composites, Electronic materials, Nano-structured materials.
- Selection of Materials: Classification of carbon steel, low alloy, carbon molybdenum, ferritic, austenitic and martenistic stainless steel. Selection and application of advanced alloys, stainless steels, Cr-Mo steels, Ti-alloys
- Heat Treatment and Mechanical Testing of materials including standards and specifications: Mechanical properties of materials & their evaluations as per ASTM or equivalent standards, tension, hardness, creep, fatigue (low & high cycle) & impact toughness tests.
- Metal Forming, Welding Science & Technology: Metal fabrication technologies, rolling, forging, extrusion, deep drawing and introduction to material modelling. Welding metallurgy for stainless steels, ferritic steels, dissimilar metal welds and Ti-alloys, hard-facing and repair welding.
- Metallographic Examination: Experimental techniques for characterization of microstructure (Optical, TEM/SEM and microscopic techniques) specimen preparation and evaluation of microstructure of different materials.
- Corrosion: Galvanic, Uniform, Crevice, Stress corrosion cracking, Corrosion fatigue, Corrosion fast reactors and re-processing plants, Corrosion test methods and standards.
- Non-destructive evaluation techniques for materials and components: Visual, LPT, MPT, UT, Eddy current, X-ray Radiography, Neutron, Gamma ray etc. for quality assurance and in-service inspection.
- Nuclear Fuels: Production, fabrication, properties and application of nuclear fuels (metallic fuels, ceramic fuels (oxide, mixed oxide, mixed carbide)) and heavy water. Radiation damage and post irradiation examination of core materials.

Course Outcomes:

This course enables understanding of classification, selection and application of engineering and nuclear materials, including steels, advanced alloys, polymers, ceramics and composites. It develops competence in heat treatment, mechanical testing as per ASTM standards, metal forming, welding metallurgy, corrosion behavior, metallographic examination, non-destructive evaluation techniques and nuclear fuels, including radiation damage and post-irradiation examination.

References:

1. Introduction to Materials Science for Engineers - James Shackelford
2. Physical Metallurgy Principles & Practice - V.Raghavan
3. Introduction to Solids - L.V.Azaroff
4. Structure and Properties of Materials - Wulff Series, Wiley Eastern, New Delhi
5. Materials in Nuclear Application - C.K.Gupta
6. Nuclear Chemical Engineering - Benedict and Pigford
7. Physical Metallurgy, Reed - Hill
8. Heat treatment of steel - Avener
9. Introduction to Solid State Physics - Charles Kittel (Wiley Eastern)

10. Physical Metallurgy: Principles and Practice - V. Raghavan (Prentice Hall)
11. The Physics and Chemistry of Materials - Joel Gersten and Fiedenick Smith (Wiley, Canada)
12. Fundamentals of Materials Science and Engineering - D. Callister (Wiley, Europe)

RP: Fast Reactor Physics and Shielding (35 Lecture Hrs)

Coordinator: Shri Rajeev Ranjan Prasad
(rajeevphy@igcar.gov.in)

Course Details:

- **NUCLEAR THEORY BASICS :**
  - Properties of Nuclei: Size, shape and density of the nucleus, nuclear forces, nuclear structure, binding energy, stability of nucleus, radioactivity
  - Fission Process : Spontaneous and induced fission, liquid drop model, fission neutrons, delayed neutrons, fission gammas, fission products, fission product yield, FP mass asymmetry, formation and removal of FPs in a reactor
  - Concept of Nuclear Reactor Fission energy, fission rate and reactor power, energy balance, fissile, fertile and fissionable materials, reactor materials: fuel, coolant, structure, control and shield, fission product activity after shutdown – decay heat, types of reactors
  - Interaction of Neutrons with Matter Production of neutrons, elastic and inelastic scattering, radiative capture and their significance in reactors, production of photo neutrons, transmutation
  - Concept Cross-section Microscopic and macroscopic cross-section, mean free path, Maxwell-Boltzmann distribution and its departure, structural changes caused by neutron reactions
  - Variation of Cross-section with Energy Fast, resonance and thermal ranges, 1/v law of neutron cross-section, resonance absorption, Breit-Wigner formula, Doppler effect
  - Capture to fission ratio, Eta vs E curve, conversion and breeding concepts, Thorium utilization

- **BASIC REACTOR PHYSICS-STATIC**
  - Diffusion of Neutrons: Fick's law and its validity, steady state neutron diffusion equation, concepts of neutron flux and current, interface conditions, diffusion coefficient, diffusion length and extrapolation distance
  - Chain Reaction :Four factor formula, conceptual treatment of diffusion of one group of neutrons in non multiplying and multiplying media, infinite and effective multiplication factors, bare homogeneous reactor concepts, material and geometrical buckling, sub criticality and super criticality, critical mass, non leakage probabilities in bare homogeneous cores, neutron cycle and life time in finite reactor
  - Slowing Down Process: Neutron Slowing down, slowing down power and moderating ratio of moderators, slowing down with spatial migration, Fermi age concepts, migration length, multi zone reactors, ideas of reflectors/blankets, reflector savings, form factor

- **TIME DEPENDENCE**
  - Reactor Kinetics: Time dependent neutron diffusion equation, one group kinetic equation, role of delayed neutrons, prompt neutron life time, point kinetic model to illustrate importance of delayed neutrons, reactor period, reactivity and its units
  - Core Burnup and Neutron Poisons: Burnup equations including fission products, Xenon and Samarium poisons, Xenon loads (operating and post shut down), variation of Xenon load with power and enrichment, Xenon oscillations and their control

- Reactivity Coefficients and Reactor Experiments: Temperature and void coefficients of reactivity, their relevance to reactor safety
- Techniques to control reactors, typical reactivity balance, long term burnup, fuel management, reactor control system – requirements of physics aspects, reactor shutdown mechanisms and neutron monitoring during operation and shut down
- Approach to criticality, physics measurements and calibrations/validations

- **FAST BREEDER REACTORS**
  - Introduction: Fast reactors as breeders, comparison of fast and thermal reactors, types of fast reactor, role of fast reactors in Indian nuclear power program
  - FBR Neutronics: Neutron spectrum, reaction cross-section, core characteristics, blanket characteristics, breeding potential, breeding ratio and breeding gain, doubling time, Multigroup diffusion theory methods and summary of steady state computational methods for FBR
  - Effective delayed neutron fraction and prompt neutron life time, fuel expansion and bowing, sodium void reactivity effect, Doppler reactivity effect, long term reactivity effect - in FBR
  - FBR Core Design: General features of FBR core, specific power, linear rating, burnup, fluence, requirement and choice of core materials (fuel, coolant and structural materials), test reactors, commercial fast reactors, pin diameter, core height/diameter ratio, blanket thickness.
  - Salient physics aspects of FBTR and PFBR
  - Reactor Shielding: Source of various neutron & Gamma radiation within the reactor system; Attenuation of neutrons & gamma rays; Dose rates for gamma rays for various source geometries; Buildup factors for homogeneous & multiple layer shields; Removal diffusion theory for neutron attenuation; coolant activation, heat generation. Streaming of radiation through gaps & void in the shield; description of various shielding arrangements of Indian reactors

Course Outcomes:

This course develops a strong foundation in nuclear theory, neutron interactions, fission processes, reactor kinetics and static reactor physics relevant to fast reactors. It equips students to analyze fast breeder reactor neutronics, core design parameters, reactivity effects, fuel burnup, shielding principles and radiation attenuation, with emphasis on FBTR and PFBR systems.

References:

1. S. Glasstone and S. Sesonske, Nuclear Reactor Engineering, Van Nostrand, 1963.
2. S. Glasstone and M.C. Edlund, Elements of Nuclear Reactor Theory, Van Nostrand, 1952.
3. J. R. Lamarsh, Introduction to Nuclear Engineering, Addision Wesley, NY, 1960.
4. M. El-Wakil, Nuclear Power Engineering, McGraw-Hill
5. P.P. Zweifel, Reactor Physics, McGraw-Hill, 1973.
6. Weston M. Stacy, Nuclear Reactor Physics, John Wiley & Sons, Inc.
7. A.E. Walter & A.B. Reynolds, Fast Breeder Reactors, Pergamon Press.

HP: Health Physics & Radiological Safety (25 Lecture Hrs)

Coordinator: Dr. S. Chandrasekaran
(schand@igcar.gov.in)

Course Details:

- **Introduction**

Radiation sources: Natural and Induced radioactive sources, units of radioactivity, half-life and decay constant, specific activity.

Basic interaction mechanism of a) alpha b) Beta c) Gamma/X-rays d) Neutrons with matter. Definition of various dosimetric terms (exposure, absorbed/equivalent/effective dose, concept of radiation/tissue weighting factors and their importance (SI units & new units). Concepts of Exposure measurement: Free air and Air wall chambers, Exposure-dose relationship, Bragg-Gray principle.

- **Biological effects of Radiation**

Human body: Cells, tissues and organs, structure of cell, cellular effects. Factors, which influence the damage of cell. Interaction of radiation with biological matter. Radiation effects: stochastic and deterministic. Acute and delayed effects. Types of exposure (natural, occupational, medical and public).

- **Radiation Protection and Regulations**

Importance of radiation protection program in DAE, Atomic Energy act, National and International regulatory bodies, their role and responsibilities., Radiation Protection Rules, Dose limits stipulated by these bodies. Dose limits observed in India.

Radiation protection philosophy, Principles of radiation protection, concept of ALI & DAC (with suitable problems). Fundamentals of ICRP respiratory model, entry through ingestion, GI track model.

Principles of radiation detection and monitoring: Basic operating principles of a) Gas b) Scintillation (including thermo luminescence detectors) and c) Semiconductors detectors.

Type of Radiation monitors/Radioactivity measurement methods adopted for radiation protection.

- **Radiation protection and measurement (External and Internal)**

Control of external exposures (with problems in each case). Buildup concept, shielding from alpha, beta, gamma and neutron sources. Shielding from mixed sources.

Routes of intake of radioactive material,

Radiotoxicity and classification of laboratories, design of laboratory for radioactive work, Radioactive waste classification and management. Personal monitoring, area-monitoring, air monitoring. Bioassay, whole body counting techniques. Use of personal dosimeters (TLDs, pocket dosimeters)

- **Radiation Protection procedures**

Procedures followed in radiation work places, work permits, zoning concept, contamination control methods, and rubber areas, spill pack (gloves + absorbing paper), Decontamination techniques. Precautions during radioactive source storage and handling, safety during transportation. Nature of duties and responsibilities of Radiation Safety Officer/Health Physicist.

- **Nuclear Accidents, Emergency Preparedness and Management**

  Reasons for accidents, classifications of accidents, International Nuclear Events Scale. Types of emergency, emergency preparedness.

- **Radiological aspects and Environmental Impact of FBRs**

  Radiological aspects of Fuel Cycle Facilities

- **Industrial Safety Aspects**

  Introduction to Industrial Safety (accident prevention technique, Job safety analysis, control measures), Factories Act, 1948 & Atomic Energy Factories Rules, 1996, industrial safety aspects (Physical and Chemical Hazards),Industrial safety aspects (safety in Machineries, hand tools & Material handling equipments, personal protective equipments, etc)Construction safety (includes Electrical Safety & Work Permit System)

Course Outcomes:

This course provides comprehensive knowledge of radiation sources, interaction of radiation with matter, dosimetric quantities and biological effects of radiation. It builds competence in radiation protection philosophy, regulatory requirements, radiation monitoring, internal and external dose control, radioactive waste management, emergency preparedness and industrial safety practices in nuclear facilities.

References:

1. Introduction to Health Physics – Herman Cember
2. Introduction to Radiation Protection – Alan Martin
3. IAEA Regional Basic Professional Training Course on Radiation Protection (Course jointly organized by BARC and IAEA), October 26-December 18, 1998
4. Nuclear Radiation Detection - W.J. Price
5. Radiation Detection and Measurement - G.F. Knoll
6. Biological Effects of Radiation – J.E. Coggle
7. Nuclear Radiation Detectors by S.S. Kapoor and V.S. Ramamurthy (Publication: New Delhi, Wiley Eastern Ltd, 1986)
8. Atoms, Radiation and Radiation Protection by James E. Turner 1986
9. Problems and solutions in Radiation Protection by James E. Turner, 1988
10. Guide Lines for Hazard Evaluation Procedures – American Institute of Chemical Engineers
11. Risk Analysis in the Process Industries: The Institute of Chemical Engineers, England.
12. Loss Prevention in The Process Industries: Hazard Identification, Assessment and Control; Vol-1, 1996 2 Edition, Frank P Lees.

NR: Nuclear Reactors (50 Lecture Hrs)

Coordinator: Shri D. Nagasivayya (dnsiva@igcar.gov.in)

Course Details:

- **Mechanical Aspects of Power Plant Engineering:**

  Basic thermal Cycle used in NPS, means of Improving cycle efficiency, Major components in thermal and Nuclear stations, Heat Balance typical calculations, Details of equipment – Steam Generators, Turbines, Condensers, Feed Water heaters, De-aerator feed pumps, condensate and other pumps: condenser cooling water system: C&I; steam pressure control, steam discharge and steam dumping features.

- **Thermal Power Reactors :**

  Layout of Nuclear Power Plant; Zoning requirements: layout of typical PHWR; description of layout in the reactor building; Special requirements for'; nuclear components regarding material selection, reliable operation with examples of pumps, valves, heat exchangers etc. operating environment (including capabilities to withstand seismic loads). Description of calandria, end shield and coolant channel (including fitting). Description of reactivity control scheme and related hardware e.g. zone control, regulating rods, absorbers, shutdown systems etc. Fuel and Fuel transfer system; Primary Heat Transport System; emergency core cooling system; Moderator system; Auxiliary System; Description of process Water, Fire Water and Ventilation system (emphasis on role played as safety support systems); Containment and associated safety systems to mitigate consequences of accidents and contain reactivity release; ultimate heat sink and heat removal paths.A brief overview of PWR, BWR and AHWR

- **Fast Power Reactors :**

  Fast Reactor Physics and Safety: Role of FBR's, breeding ratio, doubling time, core design features - Static and Dynamic, control rod design, shielding principles, Fuel management, safety.

  Overview of FBR: FBTR and PFBR. Comparison of FBRs: Core & important design parameters, comparison of core components, major primary and secondary system components.

  Core Engineering: Description, choice of core materials, Engineering design of core, High temperature design methods.

  Heat Transport Systems: Introduction, Design of IHX, SG, sodium pump, sodium piping, Decay heat removal system.

  Instrumentation & Control: FBR instrumentation requirements, Neutronic Instrumentation and failed fuel detection methods, Reactor protection instrumentation and process instrumentation.

- **Sodium Technology (NRST)**
  - **Properties of Sodium:** Physical and chemical properties, (Hazardous nature and sodium-air, sodium-water reactions), heat transfer properties, Manufacture of sodium, Heat transfer in liquid metals, Hartman effect in liquid metals
  - **Sodium Systems – General Description:** Components of a sodium system, process, cover gas system etc.
  - **Impurities in Sodium, Purification Methods:** Impurities in sodium, purification methods, impurity monitors, (plugging indicator, on-line hydrogen, oxygen and carbon monitors)
  - **Sodium System:** Components, piping and Quality Control Materials, design aspects, tanks, valves, vapor traps and other mechanical engineering aspects, sodium centrifugal pumps, high temperature piping for sodium, fabrication aspects, quality control

- **Sodium Pumps and flowmeter:** Electromagnetic pumps and flowmeter for sodium systems
- **Electrical Systems for Sodium Loops:** Electrical supply, heating systems, heater control, types of power supply
- **Instrumentation and Control:** Level, leak, flow and temperature monitoring, pressure measurement, control of process parameter in sodium systems, under sodium viewing.
- **System Operation Aspects:** Sodium system pre-commissioning checks, methods of checking all components, limiting conditions of operation, surveillance checks etc.
- **Sodium component cleaning, fire and safety**
- Sodium removal and sodium disposal methods, sodium fire and extinguishment methods, system and industrial safety aspects.

Course Outcomes:

This course enables understanding of mechanical, thermal and safety aspects of nuclear power plants, including PHWRs, fast reactors and associated systems. It develops insight into core engineering, heat transport systems, sodium technology, instrumentation and control, reactor safety systems and operational aspects relevant to both thermal and fast power reactors.

References:

11. Nuclear Power Engineering, M. EI-Wakil, Mcgraw Hill Book Co., New York.
12. Steam Power Station, G.A. Gassort.
13. Power Plant Engineering & Economics, Strosal & Vapet.
14. Central Electricity Generating Board (London), Modern Power Station Practice, Nuclear Power Generation Ed 2, Oxford, Pergamon, 1971.
15. Weisman. J. Modern Power Plant Engineering, Englewood Cliffs, Prentice Hall, 1985.
16. IAEA Directory of Nuclear Reactors, Vol. IV, Power Reactors, Vienna.
17. Fast Reactor Technology: Plant Design, J. G. Yevick, M.I.T. Press.
18. Fast Breeder Reactors, A.E. Waltor & A.B. Reynolds, Permagon Press.
19. Status of liquid metal cooled fast reactor technology, IAEA-TECDOC—1083
20. Material for Sodium Technology portion will be provided during the course.

RE: Reactor Engineering (40 Lecture Hrs)

Coordinator: Shri Sriramachandra Aithal
(saithal@igcar.gov.in)

Course Details:

- **Core design**
  - Introduction - Role of FBR, Main Characteristics of LMFBR, Sodium as coolant, Core Configuration, Definition of NSSS & BOP, Pool & Loop Type Design.
  - Fixing Size & Parameters of LMFBR - Test Reactor, Commercial & Prototype Reactor, Unit energy cost, Hot Spot temperature of Clad, Optimisation on Pin Diameter.
  - Definition of Smear Density, DPA & Burn up.
  - Fast Reactor Core – Fuel, Basic Requirements, Choice of fuel material, Candidates for Fuel, Swelling, Fabrication cost, Reprocessing, Negative Doppler coefficient, Thermal expansion, Burnup.
  - Absorber – required features, candidate materials.
  - Structural Material in Core - Requirements of Core Structural Material, Effect of Neutron Irradiation on SS, Radiation Hardening, Embrittlement, Void Swelling, Irradiation Creep, Effect of Swelling & irradiation induced creep, Efforts to reduce swelling
  - Sub-Assembly (SA) Design - Basis for Number of pins in a fuel SA, Pin spacers, Gas Plenum, Duct considerations, Volume Fraction, Assembly Length.
  - Other Subassembly design - Blanket, CSR, DSR, Reflector, Inner B_4C, Outer B_4C and Steel Shielding subassemblies.
  - Thermal Design of Fuel Pin - Thermal Analysis, Causes for fuel restructuring, Developing Analytical Model, Necessary physical parameters, Na Heat Transfer coefficient, Hot spot Analysis, Calculation of temperature distribution across fuel pin.
  - Mechanical Design of Fuel Pin - Failure Criteria for Pin, Strain Limit Approach, Cumulative Damage Fraction, Stress analysis, Cladding wastage.
  - Hydraulic Design of Core - Factors to be reviewed for Core Hydraulic Design - Hydraulic lifting force, Mixing studies, Power flattening & flow zoning, Vibration.
  - Handling of core subassemblies - Inherent problems associated with on-line fuel handling, Fresh SA Handling, Spent SA Handling.
- **Coolant circuits**
  - Selection of coolant for FBRs, thermal, transport, nuclear, chemical and other considerations. comparison between various coolants. Special characteristics of sodium. Its impact on heat transfer and structural mechanics considerations. Selection of structural materials, basis and important alloying elements
  - Main heat transport system: primary and secondary sodium system, necessity of intermediate loop. Safety Grade decay Heat removal system, Decay heat, necessity for independent system.
  - Features of major components such as intermediate heat exchangers, steam generators, sodium to air exchangers, sodium pumps, electro magnetic pumps, sodium tanks, support design for sodium components from thermo mechanical and seismic considerations, sodium valves and types

- Design criteria, Loadings to be considered, Analysis method and validation methodology
- Special characteristic of sodium piping, sodium leak, sodium fire, various types of leak detectors, continuous and discontinuous level detectors etc.
- Sodium purification loop, oxygen control, plugging indicator, cold trap, characteristics and features
- Operating experiences of fast reactors, failures and sodium leaks reported for Phenix, Monju, PFR and other fast reactors, reasons for leak and remedy.

Course Outcomes:

This course provides in-depth understanding of fast reactor core design, fuel pin thermal–mechanical analysis, hydraulic design and subassembly engineering. It equips students to analyze sodium coolant circuits, heat transport systems, component design criteria, safety considerations and operational experience of fast reactors, including failure analysis and mitigation strategies.

References:

1. Fast Breeder Reactors - Walter, A.E. & Reynolds, A.B., PERGAMON Press.
2. Fast Reactor Technology - Plant Design - Yevick, J.G., M.I.T. Press.
3. Fundamental Aspects of Nuclear Reactor Fuel Elements - Donald R. Olander, U.S.Department of Energy, 1985.

CORE COURSES

FRE1: Code Design for Pressure Vessel and Piping (30 Lecture Hrs)

Coordinator: Shri S. D. Sajish
(sajish@igcar.gov.in)

Course Details:

- Membrane theory for thin shells, stresses in cylindrical, spherical and conical shells, dilation of above shells, general theory of membrane stresses in vessel under internal pressure and its application to ellipsoidal and torispherical end closures.

- Thick cylinder and sphere and derivation of Lame's equations. Derivation of ASME Sec. VIII Div. 1 & Div -2 equations for cylindrical spherical and conical shells, ellipsoidal and torispherical end closures.

- Bending of circular plates and determination of stresses in simply supported and clamped circular plate. Basis of ASME equation for flat closures.

- Openings, nozzles and external loading. Stress concentration in plate having circular hole due to bi-axial loading. Theory of reinforced opening and reinforcement limits.

- Beam on elastic foundation and its application to thin-walled pressure vessels. Extent and significance of load deformation on pressure vessel. Reinforcement rules for ASME, Sec. VIII Div.1. Local Stresses in shells due to external loadings from nozzles and lugs etc.

- Bolted Flanged joints. Types of flange joints. Types of gasket and their selection. Bolting design. Flange loads and moments. Design of flange as per ASME Boiler and Pressure Vessel and B 31.3 Code.

- Supports for vertical and horizontal vessels. Design of base plate and support lugs. Types of anchor bolt, its material and allowable stresses. Design of saddle supports.

- Buckling of vessels under external pressure. Elastic buckling of long cylinders, buckling modes, Buckling (collapse) coefficients. ASME procedure for design of vessels under external pressure. Design for stiffening rings. Design of shells for axial compression.

- Derivation of TEMA Design equation for tube sheets. Background of the ASME design rules for tube sheets.

- Piping thickness as per ANSI ASME B31.1 and B31.3 piping code. Flexibility factor and stress intensification factor. Design of piping system as per B31.1 piping code. Design of piping for hazardous fluid as per B31.3

- Design consideration for pressure vessel. Design pressure and temperature, Allowable stresses, Impact toughness requirement as per ASME Sec. VIII Div.1 code. Non-destructive examination of welds as per ASME Sec.VIII, Div.1 code. Difference between Sec. VIII Div.1 & Div.2.

Course Outcomes:

This course develops the ability to analyze and design pressure vessels, shells, end closures, nozzles, flanges, supports and piping systems using membrane theory, thick cylinder theory, bending of plates and buckling concepts. It equips students to apply ASME Section VIII Div.1 & Div.2, ASME B31.1 and B31.3 codes, including allowable stresses, NDE requirements, reinforcement rules and design for external pressure.

References:

1. Harvey J F , 'Pressure vessel design' CBS publication.
2. Brownell. L. E & Young. E. D , 'Process equipment design', Wiley Eastern Ltd., India.
3. ASME Pressure Vessel and Boiler code, Section VIII Div 1 & 2, 2003.
4. American standard code for pressure piping , B 31.1.
5. Standards of Tubular Exchanger Manufacturers Association, Eighth Edition ,1998.

FRE2: Heat Transfer and Computational Fluid Dynamics (30 Lecture Hrs)

Coordinator: Shri U.Parthasarathy
(ups@igcar.gov.in)

Course Details:

- **Basic equations:** Kinematics of fluid flow. Streamline, streakline and pathline; stream function, vorticity & deformation of a fluid element. Basic equations governing heat conduction, fluid flow & mass transfer (viz. the continuity, momentum and energy equations) with special reference to Navier-Stokes & Bernoulli equations.
- **Laminar Boundary Layer and Forced Convection:** Formulation of differential equations for hydrodynamic and thermal boundary layers. Different analytical methods for reduction of boundary layer equations and theoretical formulation for boundary layer thickness. Study of jets and flow separation in the light of Boundary Layer Theory. Convective heat transfer in internal and external flows. Low and high Prandtl number limits and different thermal boundary conditions.
- **Turbulent Flow and Heat Transfer**: Reynolds decomposition for turbulence. Prandtl's mixing length theory, Mixing length models. Structure of turbulent boundary layer over flat plate and through circular cylinder. Calculation of friction factor and drag coefficient. Analytical and semi-analytical correlations for heat transfer coefficients. Analogy between heat and momentum transfer. Reynolds analogy, von Karman-Prandtl analogy, Martenelli analogy, Lyons analogy.
- **Natural Convection**: Basic Equations of natural convection. Boussinesq approximation. Derivation of dimensionless groups from basic equations. Analytical approximations.
- **Principles of heat transfer in porous media**: Single phase flow in porous medium Darcy Law, porosity & permeability, homogenization method, continuity equation & energy equation.
- **Heat Transfer with Phase Change**: Introduction of two phase flow and basic relations; flow regimes in adiabatic and diabatic vertical co-current flow and in adiabatic co-current horizontal flows. Basic equations of two phase flow; Homogenous & separated flow models for two phase flow, void fraction & phase velocity ratio (Zivi's model). Introduction to boiling heat transfer and bubble nucleation; Regimes in boiling heat transfer (a) pool boiling & (b) flow boiling: Heat transfer correlations for pool boiling (Rohsenow's correlation) and flow boiling (Chen's correlation). Condensation heat transfer: Nusselt's theory and its limitations: Jet condensation fundamentals and its application in containment cooling. Critical heat flux: Various models of critical heat flux, CHFR, MCHFR Critical power concept. Post-dryout heat transfer. Various models available for calculation of heat transfer coefficient. Critical Flow. Models for single - phase and two-phase critical flows.
- **Radiation heat transfer**: Radiation heat transfer. Reflection, absorption, transmission and emission; concept of black and grey bodies; total emissive power and Stefan-Boltzmann constant. Kirchoffs law. Shape factor & law of reciprocity; Radiation heat transfer between two grey bodies
- **Numerical Methods in Heat Transfer**: Discretization of conduction equation with Dirichlet & Neumann boundary conditions; Temporal integration: Explicit & Implicit schemes. Discretization of convection-diffusion equations (Upwind & Exponential schemes). Estimation of flow field: stream function-vorticity formulation and primitive variable formulation. SIMPLE family of algorithms. Turbulence Modeling: Eddy diffusivity models: k-ε and k-ω models. Reynolds stress models: algebraic & differential versions. Large eddy simulation and Director numerical simulation.

Course Outcomes:

This course provides in-depth understanding of momentum, heat and mass transfer phenomena, including boundary layer theory, turbulent flow, natural convection, boiling, condensation, radiation and two-phase flow. It develops competence in numerical methods, finite volume discretization, SIMPLE algorithms and turbulence models (k–ε, k–ω, LES) for CFD-based thermal–hydraulic analysis.

References:

AHMT

1. Fox. J. A, Introduction to Engineering Fluid Mechanics, New York, Mc Graw Hill, 1974.
2. Frank M White, Fluid Mechanics, 5th Edition, Boca Raton, CRC Press, 2000.
3. Cengel Y.A, Introduction to Thermodynamics and Heat Transfer, New York, Mc Graw Hill, 1997.
4. Frank P. Incropera, David P. DeWitt, Fundamentals of Heat and Mass Transfer, 5th Edition, New York, John Wiley & Sons, 1996
5. Adrian Bejan, Convection Heat Transfer, New York, John Wiley & Sons, 2004.
6. Wilcox. D.C, Turbulence Modeling for CFD, California, Dcw Industries, 1993.
7. Pope S.B, Turbulent Flows, Cambridge, Cambridge University Press, 2000.
8. Stephan K, Heat Transfer In Condensation Boiling, Berlin, Springer Verlag, 1992.
9. Tong. L.S, Boiling Heat Transfer And Two Phase Flow, New York, John Wiley & Sons, 1966.
10. P.B. Whalley, Two-Phase Flow and Heat Transfer, Oxford Press, 2005.
11. Hetsroni G, Handbook of Multiphase Systems, Washington, Hemisphere, 1982.
12. Hewitt. G.F, Process Heat Transfer, Boca Raton, CRC Press, 1994.
13. Collier. J.G, Convective Boiling and Condensation, London, Mc Graw Hill, 1972.

CFD

1. An Introduction to Computational Fluid Dynamics: The Finite Volume Method - H.K. Versteeg and W. Malalasekera, Addison-Wesley Longman, Limited, 1995, Reprinted in 1996.
2. Numerical Heat Transfer and Fluid Flow - S.V. Patankar, McGraw-Hill, 1981.
3. Computational Fluid Flow and Heat Transfer – K.Muralidhar, T.Sundararajan, Narosa Publishing - New Delhi, 2003 (IIT Kanpur series of advanced texts).
4. Heat Transfer- J.P.Holman, 9th Ed., McGraw Hill, NY.
5. Convective boiling and condensation- J.G.Collier, McGraw Hill, London,1972.

FRE3: Advanced Mass Transfer (30 Lecture Hrs)

Coordinator: Shri Sourabh Agarwal (sourabh@igcar.gov.in)

Course Details:

- **Momentum Transport:**
  - **Viscosity and Mechanisms of Momentum Transport**: Generalized Newton's Law of Viscosity, Pressure and Temperature Dependence of Viscosity, Molecular Theory of the Viscosity of Gases and Liquids, Viscosity of Suspensions and Emulsions, Convective Momentum Transport.
  - **Velocity distributions with two independent variables**: Time-Dependent Flow of Newtonian Fluids, Flow near Solid Surfaces by Boundary-Layer Theory.
  - **Macroscopic Balances for Isothermal Flows:** Macroscopic mass, momentum, mechanical energy balances; Estimation of viscous loss, Performance of Liquid-Liquid Ejector, Thrust on pipe bends**.**

- **Energy Transport:**

Fourier's Law of Heat Conduction; Thermal Conductivity, its measurement & its dependence on temperature / pressure. Theory of thermal conductivity of gases, gas mixtures and liquids, Effective thermal conductivity of composite solids, Convective transport of energy.

- **Mass Transport:**
  - **Diffusivity and the Mechanisms of Mass Transport:** Fick's Law of Binary Diffusion, Diffusivity, its measurement & its dependence on temperature / pressure, Theory of diffusion in gases, binary liquids, colloids etc. Molar transport by convection.
  - **Concentration Distributions in Solids and Laminar Flows:** Diffusion through Gas Films, homogenous / heterogeneous chemical reactions, Diffusion into a Falling Liquid Films.
  - **Equations of Change for Multi-component Systems:** Equations of Continuity for a Multi-component Mixture, Multi-component Equations of Change, Multi-component Fluxes and their applications.
  - **Concentration Distributions with More than One Independent Variable:** Time-Dependent Diffusion, Steady-State Transport in Binary Boundary Layers, Boundary Layer Mass Transfer with complex interfacial motion. Concentration Distributions in Turbulent Flows.
  - **Interphase Transport in Nonisothermal Mixtures:** Definition of Transfer Coefficients in One Phase, Analytical Expressions for Mass Transfer Coefficients, Correlation of Binary Transfer Coefficients in One Phase, Transfer Coefficients in Two Phases, Mass Transfer and Chemical Reactions, Combined Heat and Mass Transfer by Free Convection, Effects of Interfacial Forces on Heat and Mass Transfer, Transfer Coefficients at High Net Mass Transfer Rates.
  - **Other Mechanisms for Mass Transport:** Equation of Change for Entropy, The Flux Expressions for Heat and Mass, Concentration Diffusion and Driving Forces, Applications of the Generalized Maxwell-Stefan Equations, Mass Transport across Selectively Permeable Membranes, Mass Transport in Porous Media.

Course Outcomes:

This course builds a rigorous foundation in momentum, energy and mass transport using microscopic and macroscopic balance equations. It enables analysis of diffusion, convection, multicomponent transport, interphase mass transfer, chemical reactions, porous media and Maxwell–Stefan formulations, including coupled heat and mass transfer phenomena.

References:

1.Bird, R.B, Stewart, W.E. and Lightfoot, E.N., Transport Phenomena, Wiley, 1994.
2.Denn, M.M, Process Fluid Mechanics, Prentice Hall, 1980.
3.Whitaker, S., Fundamental Principles of Heat Transfer, NewYork, Pergamon, 1997.
4.Cussler, E, L., Diffusion: Mass Transfer in Fluid Systems, Cambridge, 1985
5.Welty, J.R., C.E. Wicks and R.E. Wilson - " Fundamental of momentum, heat and mass transfer ", John Wiley and Sons, 1976.

6.Sissom, L.E. and D.R.Pitts - " Elements of Transport Phenomena ", McGraw Hill, New York, 1972.

7.Brodkey, R.S. and H.C.Hershey - " Transport Phenomena ", A United Approach McGraw Hill, 1988.

FRE4: Reliability Engineering (20 Lecture Hrs)

Coordinator: Dr.M.Ramakrishnan (mramki@igcar.gov.in)

Course Details:

- Reliability Mathematics- Fundamentals of probability, Random Variables and their probability distributions, common distribution functions, Uniform, Normal, Lognormal, Exponential and Extreme value distribution, correlations, Regression analysis, Bayesian Methods, Functions of Random Variables, Central Limit theorem
- Elements of Component Reliability – Definition of reliability, Availability and risk, Basic Component reliability model, Failure rate & hazard rate, Life testing, Component reliability.
- Reliability in Engineering Design – Limit state, Probability of failure, Monte Carlo simulation method, Generation of Uniform Random Number, Generation of Normal Random Number, General procedure of generating random numbers from an arbitrary distribution, Accuracy of probability estimates, Reliability Index, First Order Second Moment Reliability estimates, Reliability Index, First Order Second Moment Reliability Index, Hasofer Lind Reliability Index, Rackwitz Fiessler procedure, Correlated random variables.
- Probabilistic Fracture Mechanics – Brief overview of failure modes for flawed structures, linear elastic fracture mechanics, net section collapse, R6 method, fatigue analysis, crack growth analysis, Application of PFM to nuclear structural components.
- System Reliability Analysis – Elements and systems, series and parallel systems, Reliability bounds on structural systems, Failure mode and Effect analysis, Reliability block diagram, Redundancy techniques in system design, Fault tree and Event tree analysis, Reliability and availability of repairable systems.
- Application of Reliability – PSA of Nuclear Plants, Identification of initiating event, Event sequence modeling, system modeling, input data analysis including common cause failure and human reliability data quantification, determination of Core Damage. Frequency and its significance. Internal and External events, Reliability centered maintenance, Risk based in-service inspection strategies, Important measures, Risk based ranking matrix.

Course Outcomes:

This course equips students with the ability to quantify reliability, availability and risk using probability theory, statistical distributions and reliability indices. It develops skills in Monte Carlo simulation, probabilistic fracture mechanics, fault tree and event tree analysis, and application of PSA, reliability-centered maintenance and risk-based inspection in nuclear systems.

References:

1. Reliability and Maintainability Engineering, Charles.E.Ebeling, Tata- McGraw Hill, 2000.
2. Fracture Mechanics- Fundamentals and Applications, T.L.Anderson , CRC Press, 2005.
3. Lecture Notes-Topics in Solid Mechanics-Reliability Analysis and Design, Sharit Rehman, 1999.
4. Structural reliability analysis and prediction-R.E.Melchers, Ellis Horwood Limited, 1987.
5. Probablistic Safety Assessment in Chemical and Nuclear Industry-R.R.Fullwood, BH, Oxford, 2000.
6. Probability, reliability and statistical methods in engineering design – Halder. A and Mahadevan.S., 2000, John Wiley & Sons, Newyork.
7. Introduction to reliability engineering - E.E. Lewi, John Wiley, NY, 1987
8. An introduction to reliability and maintainability engineering, Tata-Mcgraw hill, New Delhi 2000.
9. Probabilistic structural mechanics handbook – C(Raj) Sundararajn, 1995, Chapman and Hall, NY

FRE5: Process Design and Control (30 Lecture Hrs)

Coordinator: Dr. K. A. Venkatesan
(kavenkat@igcar.gov.in)

Course Details:

- Distinctive characteristics of dynamics of chemical process systems; process control objectives and stra balance and product quality control Review of dynamic behavior of linear systems and their control Linear processes with difficult dynamics.
- Nonlinear process dynamics; phase-plane analysis; multiple steady-state and bifurcation behavior; Process Identification; Controller design via frequency response analysis; Model based control; Cascade, feed forward & ratio control; Controller design for nonlinear systems; Introduction to multivariable systems. Interaction analysis and multiple single loop design.
- Design of multivariable controllers; Introduction to sampled-data systems; Tools of discrete-time systems analysis; Dynamic analysis of discrete-time systems; Design of digital controllers; Introduction to model predictive control; Convolution models; Model predictive control of MIMO systems

Course Outcomes:

This course develops understanding of dynamic behavior of linear and nonlinear process systems, including process identification and controller design. It equips students to design multivariable, digital and model predictive control systems, applying frequency response methods, cascade, feedforward and MIMO control strategies.

References:

1. Buckley P.S., Techniques of Process Control, John Wiley, 1964.
2. Douglas, J.M., Process Dynamics and Control, Vols, I & II, Prentice Hall, 1972.
3. Stephanopoulos G., Chemical Process Control, Prentice Hall, 1988 Current Literature.
4. Emanule, S.Savas - " Computer Control of Industrial Processes ", McGraw-Hill London, 1965.
5. Peter Harrior - " Process Control ", Tata McGraw Hill publishing Co., Ltd., New Delhi., 1977

FRE6: Vibration Engineering and Condition Monitoring (20 Lecture Hrs)

Coordinator: Shri S. Chandramouli (mouli@igcar.gov.in)

Course Details:

- Single-degree-of Freedom (SDOF) Systems: Free vibration equation of motion; Concept of natural frequency; Solution of equation of motions for undamped and damped free vibrations – underdamped, overdamped and critically damped systems; Material and structural damping – evaluation of damping in SIDOF systems' Response to harmonic loading – complementary solution and particular solution; Response to periodic loadings using Fourier Series, Response to general dynamic loading – Duhaml's Integral.
- Multi-Degree-of Freedom (MDOF) Systems: Equations of motion – lumped mass and distributed parameter systems; Eigen value problem, concepts of Eigen values and eigenvectors; Normal mode vibrations – Free and forced; Orthogonality conditions; Mode superposition method & Direct integration methods; Vibration of continuous systems; Vibration absorption, vibration isolation and dampers, transmissibility and isolation efficiency.
- Response of Systems to Ground Motion: Earthquake motion – Safe shutdown Earthquake (SSE) and Operating Basis Earthquake (OBE); Magnitude and Intensity of an earthquake; Design basis earthquake – Design Time History and Design Response Spectra; Response Spectrum Method and Time History Method of Analysis – Concept of Mode participation factor, modal Combination and spatial combination rules; A seismic design of equipments and piping systems as per ASME Sec.III Appendix-N
- Rotor Dynamics: Basic Concept: a) Critical speed, b) Unbalance response; Whirling of rotating shaft – Jeff Cott rotor; Phase-amplitude relationship, effect of damping; Amplitude build up at critical speed; Effect of support flexibility; Performance verification of rotating machinery.
- Dynamic Balancing: Static and Dynamic unbalance; Single plane and two plane balancing; Sources of unbalance; Method of mass correction and balancing practice; Balancing quality standards and specification for rotors; Classification of rotors and type of balancing required.
- Flow Induced Vibration: Fluid-Flow across smooth circular cylinder and in an array of cylinders; Strouhal number, Added Mass; Models and analysis for vortex-induced Vibration; Sources of Vibration in pipes containing fluid; Codes and standards applicable for flow induced vibrations.
- Vibration Measurement and Signal Analysis: Types of transducer, their principle and application ranges; Accelerometer, Eddy current transducer and LVDT, Modes of vibration measurement (Displacement, Velocity and acceleration); Characterization of periodic, periodic and random signals; Fourier Spectrum, Power spectrum, Cross-power spectrum, coherence, auto and cross – Correlation and significance of these parameters; Application of vibration of condition monitoring and diagnostics; Vibration standards for acceptance.

Course Outcomes:

This course provides comprehensive knowledge of free and forced vibrations of SDOF and MDOF systems, including modal analysis, seismic response, rotor dynamics and flow-induced vibration. It develops practical competence in vibration measurement, signal analysis, balancing techniques and condition monitoring for machinery diagnostics and acceptance as per standards.

References:

1. Theory of Vibration with Applications, William T. Thomson, CBS Publishers & Distributors, 1988.
2. Mechanical Vibration Practice with basic theory – V. Ramamurti, Narosa publishing house, Chennai.
3. Vibration measurement and analysis - B.C. Nakra, G.S.Yadava, L.Thuestad, National Productivity council.
4. Flow-induced vibration – Robert D. Blevins, Krieger publishing, Latest edition.
5. Machinery vibration - Victor Wowk, Tata Mcgraw hill publishers, Latest edition
6. Machinery malfunction diagnosis and correction – Robert C. Eisenmann, Pearson education publications, Latest edition.
7. Practical machinery management for process plant – H.P. Bloch, vol 2, Gulf publishing company, London, Latest edition.
8. Engineering applications of correlation and spectral analysis – Bendat J.S. and Piersom A.G., John wiley publications, Latest edition.

FRE7: Seismic Design of Nuclear Reactors and Facilities (30 Lecture Hrs)

Coordinator: Shri S. D. Sajish
(sajish@igcar.gov.in)

Course Details:

- **Introduction to Earthquakes:** Tectonic features, faults e.g., plate boundaries, intra faults, horizon of earthquakes, Definition of various terms e.g., focus, epicenter distances, energy release, relations of magnitude v/s energy, magnitude v/s peak ground accelerations, definition of various waves generated e.g., p-waves, recording of earthquake motions, strong motions, attenuation relations.
- **Design Basis Ground Motion and IS 1893 Spectra:** Selection of design magnitudes of earthquakes, Evaluation of peak ground accelerations, return/recurrence periods, spectral shapes, synthetic time histories, peak ground accelerations for various zones of India.
- **Introduction to Earthquake Engineering:** Equations of motion for simple systems, importance of inertia forces, elastic forces, energy dissipation and damping, natural frequencies, mode shapes, modal participation factors, evaluation of seismic forces for single and two degree freedom systems.
- **Analysis Procedures for multi degree freedom systems:** Formation of matrices for stiffness, mass and damping. Frequency evaluation methods-subspace iteration, lanczos. Response spectrum analysis-modal combinations. Time history analysis- Wilson-q, Newmark-b
- **Soil-Structure Iteration:** General requirements, types of foundations, evaluation of subsurface material properties such as shear modulus, material damping ration, Poisson's ration etc. Analyses-direct method, impedance method, foundation uplift analysis.
- **Analysis and design of Structures:** Modeling of structures considering soil-structure interaction, structure-equipment interaction, damping of the structures, analysis of structures, evaluation of seismic forces, design of structures for seismic loads.
- **Analysis and design of Equipment:** Modeling of equipment, structure-equipment interaction, equipment-piping interaction, damping of the structures, analysis of structures, evaluation of seismic forces, design of structures for seismic loads.
- **Analysis and design of Piping:** Modeling of piping, equipment-piping interaction, damping of the piping, analysis of piping, evaluation of seismic forces, and design of piping for seismic loads.
- **IS 1893, 2002, Indian Standard Criteria for earthquake resistant design:** Seismic Coefficient method, Importance factors for industrial systems, response reduction factors, ductility design provisions, seismic design of chimneys, towers as per IS 1893.
- **Testing:** Pseudo-dynamic testing, shake table testing, in situ testing, ambient testing, testing for functional requirements, determination of natural frequencies and damping.
- **Response Control and Retrofitting:** Merits of response control design, passive (EPD, LED, base isolation etc) and active control, various devices of active and passive control, various retrofitting techniques, FRP wrapping, steel plate wrapping.
- **Seismic Design of Nuclear Facilities:** Earthquake resistant design of nuclear facilities with limited radioactivity inventory such as Research Reactors, `Waste Management Plants suing IAEA-TECDOC-348, Design of nuclear fuel cycle facilities using IAEA-TECDOC-1250.
- **Seismic re-qualification of old plants:** Inelastic response spectra, push over analysis, retrofitting techniques.
- **Tutorials:** Simplified models for structures like towers, chimneys, simple frames, equipment like heat exchangers, pressure vessels and piping considering various support conditions like fixed-fixed, fixed-free, pin-pin, evaluation of seismic responses using first fundamental modes or peak values of design response spectrum.

- **High Temperature and Creep Fatigue Interaction:** Damage mechanisms and failure modes, Time-dependent and frequency-dependent damage, Cumulative damage rules, Different approaches for life prediction under creep-fatigue conditions: Frequency-modified approach, strain range partitioning (SRP), Ductility exhaustion method, Creep-fatigue interaction Diagram, Thermomechanical fatigue, Codes and Standards

Course Outcomes:

This course enables analysis and design of structures, equipment and piping systems under seismic loads using response spectrum and time history methods. It develops understanding of soil–structure interaction, IS 1893 provisions, seismic qualification, retrofitting techniques and IAEA/AERB guidelines for nuclear facilities.

References:

1. Chopra, A.K., “Dynamics of Structures, Theory and applications to Earthquake Engineering”, Pearson Education Inc., 2003.
2. Ray W.Clough and Joseph Penzien, Dynamics of Structures”, New York, McGraw-Hill Book Company.
3. Mariopaz, “Structural Dynamic (Theory and Computation)”, CBS Publishers and Distributors, Delhi.
4. Bathe, K.J., and Wilson, E.L., “Numerical Methods in Finite Element Analysis”, Englewood, N.J., Prentice-Hall.
5. ASCE 4-98, “Seismic Analysis of Safety Related Nuclear Structures and Commentary”, ASCE, New York.
6. United States Nuclear Regulatory Commission (USNRC), 1990, Standard Review Plan
7. P.N. Agarwal, “Engineering Seismology”, IBH Publishers, New Delhi.
8. Safety Guide, AERB/SG/D-23, “Seismic Qualification of structures, Systems and Components of PHWRS.
9. AERB/SG/S-11, 1990, “Seismic Studies and Design Basis Ground Motion for Nuclear Power Plant Sites”. AERB, Mumbai, India.
10. IS: 1893 (Part 1,2 & 4) 2002, criteria for Earthquake Resistant Design”, BIS, New Delhi**.**

FRE8: Emergency Preparedness and Disaster Management (20 Lecture Hrs)

Coordinator: Dr. Vidya Sundararajan
(vidya@igcar.gov.in)

Course Details:

- **Emergency Preparedness**
  Bases and contents of emergency response plan by operating organization, Classification of emergencies - Emergency Standby - Personnel Emergency - Plant Emergency Site Emergency - Off-Site Emergency, Organisation for emergency response – Plant Emergency organization - Site Emergency Organisation – Off-Site Emergency Organisation., Emergency measures – Notification - assessment action during emergency - Corrective Actions - Protective Measures - Contamination Control Measures - Termination of Emergency, Assistance to affected personnel - First-aid - Decontamination - Transportation- Medical Treatment, EMERGENCY PREPAREDNESS – Training - Exercises - Review and Updating of Plans and Procedures - Emergency Equipment and Supplies

- **Disaster Management**

- **Nuclear and Radiological Emergency/Disaster Scenarios**
  Nuclear and Radiological Emergency/Disaster Scenarios, Accidents in Nuclear Power Plants and Other Facilities in the Nuclear Fuel Cycle, 'Criticality' Accidents, Accidents during Transportation of Radioactive Materials, Accidents at Facilities using Radioactive Sources , Nuclear/Radiological Terrorism and Sabotage at Nuclear Facilities, Need for a Comprehensive National Radiation Emergency Management System , Disaster Management in India

- **Approach to Nuclear and Radiological Emergency Management**
  Strategies for Nuclear Emergency Management, Nuclear Emergency Management, Framework, Prevention of Nuclear Emergencies, Emphasis on Prevention (Risk Reduction) and Mitigation Measures, Prevention (Risk Reduction), Mitigation Measures , Compliance with Regulatory Requirements, Nuclear Emergency Preparedness, Capacity Development , Nuclear Emergency Response, Strengthening the Framework of Nuclear Emergency, Monitoring the Implementation of Nuclear/Radiological Emergency Action Plans

- **Mitigation of Nuclear/Radiological Emergencies**
  Mitigation Measures, Defence-in-Depth: Salient Features, Mitigation of Nuclear and Radiological Emergencies, Engineered Safety Features, Accident Management, General Mitigation Features, Engineered Safety Features (to Mitigate the Consequences of an Accident) in Nuclear Power Plants

Course Outcomes:

This course provides knowledge of nuclear and radiological emergency preparedness, including classification of emergencies, emergency response organization, protective measures and contamination control. It develops understanding of disaster management frameworks, defence-in-depth, mitigation measures, accident management and national nuclear emergency response systems.

ELECTIVE COURSES

FRE9: Plant Control (25 Lecture Hrs)

Coordinator: Shri M.S. Koteeswaran
(kodi@igcar.gov.in)

Course Details:

- Control Physics: Review of Reactor Kinetics - neutron power - prompt and delayed neutrons - Criticality – Reactivity Feedbacks - reactivity coefficients Sodium void coefficients;
- Reactor Control Concepts: Start-up - Operation at steady power - shutdown criteria - design considerations - reactivity disturbances and transients.
- Reactivity control devices - reactivity insertion rates – principles. Calibration of control rods.
- Plant Dynamics and Overall Control: Reactor Physics and engineering experiments
- Transient analysis concept - Routine Operating transients - Accidents such as LOCA, LOFA, reactivity excursions etc
- Thermal balance and reactivity balance calculations

Course Outcomes:

This course develops understanding of reactor kinetics, neutron power behavior, reactivity feedbacks and sodium void coefficients relevant to fast reactors. It equips students to analyze reactor start-up, steady-state operation, shutdown criteria, plant dynamics, thermal and reactivity balance, and transient and accident scenarios such as LOCA, LOFA and reactivity excursions.

FRE10: Turbine Generator Fundamentals (25 Lecture Hrs)

Coordinator: Shri M.S. Koteeswaran
(kodi@igcar.gov.in)

Course Details:

- Principles of steam turbine cycle, steam turbines, impulse and reaction turbines, Rankine cycle, velocity diagram for impulse / reaction turbine, state point locus or condition line for multistage turbine, reheat factor, Willan's line variation of stage pressure with load, heat rate, thermal efficiency, peak load, base load, spinning reserve and capacity factor.
- Turbine parts, construction of nozzle, turbine blades, turbine rotor, turbine casing, cylinder supports.
- General design aspects, output of a steam turbine, effect of higher steam inlet pressure, effect of high inlet steam temperature, effect of the size of the turbine, effect of back pressure on the economy of a turbine, effect of reheat, effect of feed water regenerating cycle, double cylinder construction speed of a turbine.
- Nuclear turbine, erosion of blades, methods of reducing moisture content, moisture removal within the turbine, external moisture separator, re-heater, protection of blades against erosions, over speeding of turbine.
- Lubrication of bearings, turbine oil system, theory of lubrication of turbine bearings, viscosity, oiliness, boundary lubrication, film lubrication, the journal bearing, hydro dynamic lubrication, hydrostatic lubrication, properties of oil, additives, treatment of oil.
- Governor theory, basic methods of governing, throttle governing, nozzle governing, difference between governor and fly wheel, types of governors, centrifugal governor, effect of friction, speed droop, speed regulation for machines operating, inertia governor, electric governor, new governing systems used in the latest NPPs.
- Turbovisory instruments, purpose of turbovisory instruments, location of Turbovisory instruments, differential expansion indicator, eccentricity recorder, turbine pedestal movement indicator, speed indicator and recorder, vibration indicator.
- Turbine commissioning, pre-start commissioning, lubricating oil system, checking tightness of vacuum system, flushing the condensate, feed water and other piping of the various sub-systems, turbine supervisory instruments, governor systems, main steam line blow out, Vacuum pulling, starting a new turbine for the first time.
- Pre-heating of turbine, cold start and hot start, heating process, heating rates, differential expansion of cylinder and rotor, effect of flanged horizontal joint, flange bolts, conditions in a standing hot turbine, turbine shaft turning gear, thermal expansion during warming up.
- Operation of turbine, start-up procedure, on-load operation, routine tests, turbine shutdown procedure.
- Turbine troubles, shaft vibration, disc vibration, blade vibration, internal defects of material, expansion of steam piping, corrosion of blades and diaphragms, turbine blade deposits.
- Protection and safety devices, turbine regulating system, turbine protective system, protections on boiler feed pumps, H.P. heaters and L.P. heaters
- Inspection and overhauling, lifting the cover, inspection of diaphragms, checking the clearances, inspection of rotor, Inspection of shafts, inspection of steam valves.
- Condensers, design of condenser, effect of changes in cooling water temp. in condenser operation, effect of varying cooling water flow on condenser back pressure, air leakage, water leakage, maintenance of condensers, condenser as a deaerator, back washing of condenser, Hoggers and methods of vacuum creation, replacement of Hoggers with vacuum pumps, reasons for this replacement and their advantages.
- Regenerative feed heating, selection of feed heating system, components of feed water system, effectiveness of feed water heater, deaerating contact heaters, deaerators, closed heaters, cascading of feed water heater drains, venting of feed water heaters, performance of feed heaters.
- Boiler feed pumps, condensate extraction pumps and controls, Boiler feed pump and controls, Boiler feed pump recirculation and up warm-up lines, Net Positive Suction Head (NPSH) for a pump, boiler feed pump

NPSH.

- Chemical control, design intent of a system chemical control, review of basis and material of construction, co-ordinated phosphate pH control, all volatile or zero solid treatment, mixed treatment, Oxygen scavenging, ferrous sulphate injection for prevention of condenser tube corrosion.
- Generator and auxiliaries, stator cooling water system, hydrogen cooling system, seal oil system.

Course Outcomes:

This course provides comprehensive knowledge of steam turbine cycles, turbine–generator construction, governing systems and lubrication practices used in nuclear power plants. It develops competence in turbine commissioning, operation, protection systems, condenser and feed heating systems, and diagnosis of turbine operational problems and safety-related issues.

FRE11: Mechanical and Electrical Equipment (25 Lecture Hrs)

Coordinator: Shri M.S. Koteeswaran
(kodi@igcar.gov.in)

Course Details:

- Bearings and Lubrication, Types and identification of bearings - Illustration of different types of bearings - Selection of bearings - Lubrication methods - Types of lubricants - Lubricant properties - Bearings and lubrication methods used in: - Turbine – Primary & Secondary sodium Pumps - Boiler feed pump Bearing mounting in motors (Horizontal and vertical) - Operating care for bearings - Causes of bearing failure.
- Seals, Types of static and dynamic seal. Gland packing - Mechanical seal - O ring – etc. Inspection of mechanical seal - Causes of failure of mechanical seals - Operating care for all the seals - Importance of seals in nuclear power plant operation.
- Power Transmission, Types of couplings and belts - Application of various couplings like tyre coupling, love joy coupling, steel flux coupling, bush and pin sliding disc, sliding block, flange muff and coupling. - Types of misalignment - Effects of misalignment on equipments.
- Pumps, Types of pumps - Centrifugal, rotary and reciprocating pumps – Pumps used in Sodium system-Construction details of pumps - Types of casing - Types of impeller - Effects of radial thrust and axial thrust - Methods of balancing of radial thrust and axial thrust - Operation of centrifugal pump, external gear pump, internal gear pump, screw pump, radial piston pump - Head - Flow characteristics of centrifugal pump - System head characteristics - Power characteristics of centrifugal pump - Effect of drooping head characteristic - Cavitations, aeration and Net Positive Suction Head (NPSH) - Series and parallel operation of centrifugal pump - Practical operation of centrifugal pump and rotary pump - Effect of direction of rotation - Primary heat transport pump - disassembly and assembly - alignment procedure - lift adjustment - Canned rotor pump details, operation and testing – Trouble shooting procedures. Vacuum pumps - Types of vacuum pumps.
- Electromagnetic Pumps – types of EM pumps – construction- characteristics- protections for EM pump-Operation of EM pumps.
- Valves and Actuators, Types of valves - gate valve - globe valve - check valve - relief valve and safety valve - butterfly valve - diaphragm valve -bellow seal valve Application of the above valves - Construction detail of valves Gland packing - Live loading - Testing of valves - Types of valve actuator - Features of actuators - Hopkinson actuator -Limitorque actuator -Rotork actuator -piston type actuator - diaphragm type actuator. Operation of the above actuators - Test procedures for valves actuators.
- Sodium system valves – bellow seal valves – frozen seal valves
- Hydraulics, Circuits and control - Hardware in hydraulic circuits -tube -pipe -fittings and connectors :- flared fitting, swagelok fitting, quick disconnect coupling.-hoses - Specifications of hardware parts - Operation and maintenance problems - Hydraulic controls, types and application of - hydraulic cylinder – pressure regulating valves - directional valves - sequence valve -decelerating valves - flow control valves - Effect of pressure and flow of hydraulic oil on actuators.
- Compressors, Types of compressors - Constructional details of - reciprocating compressor - sliding vane compressor. Blowers- Types of Blowers.
- Chillers. Types of Chillers , refrigerants, refrigeration cycles, Air handling units
- Filters, Types of filters & specifications, HEFA filters, testing of HEFA filters
- Heat Exchangers, Types of Heat Exchangers - Types of tube and tube sheet connections - General details of heat exchangers. Types of maintenance
- Piping and Tubing, and pipe fitting.
- Vibration and measurements, Causes of vibration, characteristics of vibration, significance of displacement,

velocity, acceleration, phase and frequency. Single plane balancing. Vibration measurement devices.

- **Power Systems and Electrical Equipment**

  - **Part – I: Power Systems**

Grid characteristics, Interaction of NPP with grid, Power system analysis and representation, Voltage and frequency control, Synchronous machines, synchronizing and load shedding, Main output and station service systems, Line, transformer and generator protections, Short circuit calculations, Power systems components

single line diagrams, concept of real and reactive power flows, voltage and frequency relations to real and reactive power, AC and DC transmission systems, Automatic voltage and frequency control, Definitions of related plant factors, synchronous machine theory, isolated and parallel operation, Automatic voltage regulator, Stability of alternators, steady state & transient stability, abnormal operating conditions, Excitation systems, loss of excitation, loss of synchronism, current unbalance, switchyard concepts, Station service and unit transformer arrangements, Classes of power supplies, standby systems, Automatic and emergency transfer schemes, Transformer, switchgear and protective relaying concepts, specific relaying for generators, motors, transformers, buses and transmission lines.

  - **Part – II Electrical Equipment**

Electrical control components and circuit checks. (415V / 3.3kV / 6.6KV), Principles of electrical control, control circuit components like relays, contactors, switches, fuses, control transformers, indicating lights, terminal blocks, control cables, Reading of electrical drawings, Local and remote controls, interlocks, push buttons, types of hand switches, forward / reverse controls, resetting meaning of logic, auto and standby modes, motor control centres (MCCs), MCC types, parts, construction, Pump, valve, crane, diesel generator controls, synchronizing controls, circuit breaker controls,

Various types of starters and controls (D-O-L), Star- Delta (manual and automatic)

- Electrical test equipment in commissioning checks.
- Use of test equipment in commissioning including - Meggers, Motor Rotation Testers - Phase Sequence Indicators - Transformer Turns Ratio Testers - Tachometers - Tong testers – Multimeters, Resistance bridges - Stroboscopes - Oscilloscopes – Harmonic Analyzers
- Commissioning tests on motors, generators, transformers, valve actuators, switchgear, protective relays, batteries and chargers
- Motors, Identification of motor leads - Measurement of insulation and winding resistance - Measurement of no load current, speed, bearing checks -Magnetic balance tests - Measurement of power factor
- Transformers, Polarity checks - Measurement of turns ratio, vector group - Insulation checks - No load and short circuit tests - Measurement of magnetizing current - Measurement of %impedance - Measurement of dielectric strength of insulating oil - New types of transformers – dry type transformers - On line tap changers
- Generators, Measurement of insulation and winding resistance - Starting, stopping, synchronizing, loading and unloading - Phase sequence tests, Excitation control.
- Switchgear, Measurement of contact resistance - Measurement of closing and tripping time - Measurement of contact pressures - Study of link mechanisms - Study of stored energy features.
- Valve actuators, Limit and torque switches - Valve position indicators – Types of actuators.
- Protective relays, Calibration of relays - Use of primary and secondary injection tests - Testing of time over current, thermal overload and directional relays - Study of relay test sets - Multiamp, Gyro, English Electric Makes - Solid state protective relays and their use in NPPs – Latest methods in relay testing using micro-processors.
- Batteries, Parts of lead acid cells - Measurement of specific gravity, voltage - Charging and discharging of cells - Study of charging circuits, Nickel cadmium batteries.
- High Voltage Equipment, High voltage equipment and electrical layout study of high voltage equipment

like - Current transformers - Potential transformers - Disconnect switches - Capacitor voltage transformers - Line traps - Air blast circuit breakers, SF_6 ,Circuit breakers.

- Lightning arresters.
- Switchyard layout, indoor and outdoor switchyards, problems associated with costal sites - corrosion, salt deposition, line washing.
- Uninterrupted Power Supplies (UPS), Control UPS and Power UPS, SCADA.

Course Outcomes:

This course develops in-depth understanding of mechanical equipment such as pumps, valves, seals, bearings, compressors, heat exchangers and hydraulic systems, including sodium system components. It also builds strong competence in power systems, electrical equipment, protections, commissioning tests, diagnostics and operation of motors, generators, switchgear and UPS systems in NPPs.

FRE12: Maintenance Engineering (25 Lecture Hrs)

Coordinator: Shri M.S. Koteeswaran
(kodi@igcar.gov.in)

Course Details:

- Overview of maintenance in NPPs, Challenges in NPP maintenance, Maintenance economics.
- Reliability engineering and maintenability, Definition of reliability, bathtub curve, reliability prediction for complex plant, reliability for series and parallel arrangement, Maintainability, Availability, mean time to failure, (MTTF) mean time to repair (MTTR), means adopted to improve reliability in NPP.
- Maintenance policies, Different types of maintenance policies, fixed time maintenance, condition based maintenance, opportunity based maintenance, operation to failure maintenance, design out maintenance. Application and relative advantages and disadvantages of the policies.
- Maintenance planning, maintenance decision making, maintenance planning, manrem budgeting, determination of maintenance plan, classification and identification of equipment, equipment histories, selection of maintenance policy, preventive maintenance program.
- Spare parts management and inventory control, Requirement of the spare parts management. Economic order quality. Safety stock and when to order. Special condition for storage of sensitive spares, shelf life management.
- Condition based maintenance, Requirement, relative advantages and disadvantages, condition monitoring categories -on load and off load monitoring. Types of monitoring techniques i.e. lubricant monitoring techniques, wear debris analysis and malfunctions that can be detected by lubricant monitoring. Thermal monitoring, types of thermal monitoring, and parameters that can be detected by thermal monitoring.
- Vibration monitoring, basic characteristics, analysis, vibration meter construction, factors contributing to vibration monitoring.

Course Outcomes:

This course equips students with knowledge of maintenance strategies, reliability, maintainability and availability concepts applied to nuclear power plants. It emphasizes maintenance planning, spare parts management, preventive and condition-based maintenance, including vibration, thermal and lubricant monitoring techniques to improve plant performance.

FRE13: Regulatory Framework for NPPs (25 Lecture Hrs)

Coordinator: Dr. S. Chandrasekar (schand@igcar.gov.in)

Course Details:

- The Atomic Energy Act 1962 and the Factories Act 1948, Salient features of the Act covering the major provisions and including brief title, scope of application, appropriate government, ownership, processing and usage of radioactive materials, authorisation for power generation and storage of certain chemicals, regulating and enforcing bodies under the Act. Salient features of the Factories Act 1948 with particular emphasis on safety and welfare provisions, inspection of factories and returns needed to be filed. Salient features of the Atomic Energy (Factories) Rules 1996 and authorisation for safe disposal of radioactive waste.
- The Atomic Energy Regulatory Board (AERB), Evolution of AERB. Statutory status, role, powers and activities of AERB. Approach to safety as defence in depth. Authorisation process - site approval, construction authorisation, commissioning authorisation, operating authorisation, life extension of NPPs, decommissioning authorisation. Regulatory inspection. Safety assessment. Role and powers of SORC and SARCOP. Staffing, training, qualification and licensing. Simulator training and human error reduction. Design review for plant modifications. Major guidelines for NPP O&M. Technical specifications. Licensing practices. Independence of the regulatory body. Periodic review of NPPs. Advisory committees of AERB. Instances requiring notification and clearances.
- Electricity Act 2003 and the Boiler Act, Salient features of the act covering the major provisions and including brief title, scope of application, appropriate government, regulation and inspection of electricity generating utilities. Training and authorisation of certain personnel.
- Environmental Protection Legislation, Introductory features of covering highlights and permissions needed by NPPs under the following acts:
- The Environmental Protection Act 1986
- The Air (Prevention and Control of Pollution) Act 1981
- The Water (Prevention and Control of Pollution) Act 1974

Course Outcomes:

This course enables understanding of the legal and regulatory framework governing nuclear power plants in India, including the Atomic Energy Act, AERB regulations, Electricity Act and environmental legislation. It develops awareness of licensing processes, safety assessment, regulatory inspections, defence-in-depth philosophy and compliance requirements for NPP operation.

FRE14: Practicals (6 Weeks)

Coordinator: Shri M.S. Koteeswaran (kodi@igcar.gov.in)

- **Turbine and Generator**
  - Class room training on Generation Plant, Steam water system, Turbo- generator

- **Simulator and Fuel Handling**
  - Class room and Field Training on Fuel Handling
  - Field Training on PFBR Simulator

- **Operations**
  - **Class room Training**
    - Reactor System: Reactor Assembly, Reactor Core, Control Rod Drive Mechanisms, Emergency Core Cooling Systems
    - Sodium system: Primary Sodium System, Secondary Sodium System, Sodium Purification System, Cover Gas System, Steam Generator Leak Detection System, Sodium Instrumentation
    - Control and Electrical system, Neutronic Instrumentation, Reactor Protection System, CDPS, Power Supply Systems
    - Radiation protection

  - **Field training**
    - Reactor Operation
    - Maintenance Activities
    - Technical Service Activities
    - Quality assurance & Industrial safety

TSOs will be asked present a project report and walk-through test on the above modules.

DETAILED COURSE STRUCTURE

Foundation Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	EM	Engineering Mathematics	35	2
2.	MM	Materials and Metallurgy	25	1
3.	RP	Fast Reactor Physics and Shielding	35	2
4.	HP	Health Physics and Radiological Safety	25(15 T+10 L)	1
5.	NR	Nuclear Reactors	50	3
6.	RE	Reactor Engineering	40	2
		FOUNDATION TOTAL	**210**	**11**

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	ME1	Code Design for pressure vessel & piping	30	2
2.	ME4	High Temperature Design and Inelastic Analysis	25	1
3.	ME6	Computational Fluid Dynamics	30	2
4.	ME8	Finite Element Method	30	2
5.	ME10	Advanced Heat and Mass Transfer	30	2
6.	ME13	Reliability Engineering	20	1
7.	ME14	Manufacturing Technology	40	2
		CORE TOTAL	**205**	**12**

Electives (any four)					
Sr. No	**Course Code**	**Subject Title**	**Hours**		**Credits**
			(T)	**(L)**	
1.	ME3	Structural Integrity Assessment Methods and NDE	30	-	2
2	ME5	Seismic Design of Nuclear Reactors and Facilities	20	-	1
3	ME15	Process Control & Instrumentation	20	-	1
		ELECTIVES TOTAL	**70**	**-**	**4**

FOUNDATION COURSES COORDINATOR

Course	Coordinators	Contact
EM: Engineering Mathematics	Dr. K. Natesan	22109/22856,natesan@igcar.gov.in
	Dr. V. Satish Kumar	26919/26977,vsatish@igcar.gov.in
MM: Materials and Metallurgy	Dr. Vani Shankar	21147/22805,vani@igcar.gov.in
RP: Fast Reactor Physics and Shielding	Shri Rajeev Ranjan Prasad	22737,rajeevphy@igcar.gov.in
HP: Health Physics and Radiological Safety	Dr. S. Chandrasekaran	23556.schand@igcar.gov.in
NR: Nuclear Reactors	Shri D.Nagasivayya	21232,dnsiva@igcar.gov.in
RE: Reactor Engineering	Shri Sriramachandra Aithal	22468/22605,saithal@igcar.gov.in

CORE COURSES COORDINATOR

Course	Coordinators	Contact
ME1:Code Design for Pressure Vessel & Piping	Shri S. D. Sajish	22795/22452,sajish@igcar.gov.in
ME4:High Temperature Design and Inelastic Analysis	Shri S. D. Sajish	22795/22452,sajish@igcar.gov.in
ME6:Computational Fluid Dynamics	Shri M. Rajendra Kumar	22313/21334,mrk@igcar.gov.in
ME8:Finite Element Method	Shri S. D. Sajish	22795/22452,sajish@igcar.gov.in
ME10:Advanced Heat and Mass Transfer	Shri M. Rajendra Kumar	22313/21334,mrk@igcar.gov.in
ME13:Reliability Engineering	Dr. M. Ramakrishnan	22611/22254,mramki@igcar.gov.in
ME14:Manufacturing Technology	Dr. M. Vasudevan	21216/22805,dev@igcar.gov.in

ELECTIVES COURSES COORDINATOR

Course	Coordinators	Contact
ME3: Structural Integrity Assessment Methods and NDE	Dr. R. Suresh Kumar	22608,suresh@igcar.gov.in
ME5:Seismic Design of Nuclear Reactors and Facilities	Shri S. D. Sajish	22795/22452,sajish@igcar.gov.in
ME15: Process Control & Instrumentation	Shri M. Saktivel	22793/22156saktivel@igcar.gov.in

FOUNDATION COURSES

EM: Engineering Mathematics (35 Lecture Hrs)

Coordinators: Dr. K Natesan(natesan@igcar.gov.in),
Dr. V. Satish Kumar(vsatish@igcar.gov.in)

Course Details:

- Computer arithmetic and errors . Types of errors, error estimates and its propagation, Data analysis : Difference tables, Interpolation methods of Lagrange and Hermite, Chebyshev polynomials and Pade's approximation with rational functions. Numerical differentiation of interpolating polynomials. Numerical Integration : Trapezoidal, Monte-Carlo and Gaussian Quadrature methods Solution of algebric and transcendental equations, Newton-Raphson method, Graffe's root squaring method; Data approximation by method of least square, curve fitting.
- Linear vector space and subspaces, Basis, Gram-Schmidt orthogonalization, Linear system of equations: LU decomposition, Cholesky factorization and Gauss-Jordan technique. Iterative techniques using the methods of Jacobi, Gauss-Seidel and over relaxation. Convergence criteria and error estimation. Matrix inverse, Ill conditioned and sparse matrices. Bilinear forms, Principal axes transformation and eigen values, Determination of eigen values and eigen vectors. LU and QR algorithms, Singular matrices and singular value decomposition.
- Ordinary differential equations, Different types of differential equations, Lipschitz theorem and conditions for existence and uniqueness of solutions, Numerical methods for solving differential equations. Method of Euler, Adams and Runge Kutta, Predictor corrector method, Solving stiff equations.
- Probability and Statistics:Probability and Random variables, Binomial, Poisson and Normal distributions, Moments of a distribution, Counting experiments Estimation of model parameters, Confidence intervals, Testing of hypotheses, Goodness of fit, Chi-square test.
- Integral Transforms: Laplace transform, Linearity of LT, LT of derivatives and integrals, Solution of differential equations using LT, Response of electric circuits, Response of damped oscillator to a square wave, Differentiation and integration of LT.Periodic functions, Fourier series representation of functions, Even and odd functions, Determination of coefficients, Fourier integrals. Data compression, Hauffman coding and wavelet transforms.
- Partial Differential Equations, Finite difference method in one and two dimensions, Solution of steady and transient heat conduction and diffusion equations.
- Finite element method, Energy Theorem and integral equations, Weighted residual approximations, Point and subdomain collocation. Galerkin method, Variational principles and Lagrange multipliers. B-splines,Bezier curves, Response surface method, different levels of factorial design.

Course Outcomes:

This course equips students with strong foundations in numerical methods, linear algebra, differential equations, probability and statistics, integral transforms, PDEs and finite element methods. Learners develop the ability to analyze computational errors, solve engineering problems using interpolation, matrix methods, ODE/PDE solvers, stochastic models and transform techniques, and apply mathematics to engineering and reactor systems.

References:

1. Davis, H. T. and Thompson, K., Linear Algebra and Linear Operators in Engineering: with Applications in Mathematica, Academic Press, 2000.
2. Chapra, S.C. and Canale, R.P., Numerical Methods for Engineers, McGraw-Hill, 1985.
3. R. L. Burden and J. D. Faires, Numerical Analysis, 6th ed., PWS-Kent Publishing, 1997.
4. Krishnamurthy, E. V., Computer based numerical algorithms, East West Press, 1976.
5. Gupta, S.K., Numerical methods for Engineers, Wiley (1995).
6. Press, W.H.; Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., Numerical Recipes in Fortran (or C), Cambridge University Press (1992).
7. Scarborough, J. B. Numerical Mathematical Analysis, Oxford and IBH Publishers, 1968.

MM: Materials and Metallurgy (25 Lecture Hrs)

Coordinators: Dr. Vani Shankar
(vani@igcar.gov.in)

Course Details:

- Classification of Materials: Structure, Ferrous and non-Ferrous metals, Polymers, Ceramics, Composites, Electronic materials, Nano-structured materials.
- Selection of Materials: Classification of carbon steel, low alloy, carbon molybdenum, ferritic, austenitic and martenistic stainless steel. Selection and application of advanced alloys, stainless steels, Cr-Mo steels, Ti-alloys
- Heat Treatment and Mechanical Testing of materials including standards and specifications: Mechanical properties of materials & their evaluations as per ASTM or equivalent standards, tension, hardness, creep, fatigue (low & high cycle) & impact toughness tests.
- Metal Forming, Welding Science & Technology: Metal fabrication technologies, rolling, forging, extrusion, deep drawing and introduction to material modelling. Welding metallurgy for stainless steels, ferritic steels, dissimilar metal welds and Ti-alloys, hard-facing and repair welding.
- Metallographic Examination: Experimental techniques for characterization of microstructure (Optical, TEM/SEM and microscopic techniques) specimen preparation and evaluation of microstructure of different materials.
- Corrosion: Galvanic, Uniform, Crevice, Stress corrosion cracking, Corrosion fatigue, Corrosion fast reactors and re-processing plants, Corrosion test methods and standards.
- Non-destructive evaluation techniques for materials and components: Visual, LPT, MPT, UT, Eddy current, X-ray Radiography, Neutron, Gamma ray etc. for quality assurance and in-service inspection.
- Nuclear Fuels: Production, fabrication, properties and application of nuclear fuels (metallic fuels, ceramic fuels (oxide, mixed oxide, mixed carbide)) and heavy water. Radiation damage and post irradiation examination of core materials.

Course Outcomes:

This course enables understanding of classification, selection and performance of engineering and nuclear materials, including steels, advanced alloys, polymers, ceramics, composites and nuclear fuels. It develops competence in heat treatment, mechanical testing, welding metallurgy, corrosion behavior, metallography and non-destructive evaluation for materials used in reactor and industrial applications.

References:

1. Introduction to Materials Science for Engineers - James Shackelford
2. Physical Metallurgy Principles & Practice - V.Raghavan
3. Introduction to Solids - L.V.Azaroff
4. Structure and Properties of Materials - Wulff Series, Wiley Eastern, New Delhi
5. Materials in Nuclear Application - C.K.Gupta
6. Nuclear Chemical Engineering - Benedict and Pigford
7. Physical Metallurgy, Reed – Hill
8. Heat treatment of steel – Avener
9. Introduction to Solid State Physics - Charles Kittel (Wiley Eastern)
10. Physical Metallurgy: Principles and Practice - V. Raghavan (Prentice Hall)
11. The Physics and Chemistry of Materials - Joel Gersten and Fiedenick Smith (Wiley, Canada)
12. Fundamentals of Materials Science and Engineering - D. Callister (Wiley, Europe)

RP: Fast Reactor Physics and Shielding (35 Lecture Hrs)

Coordinators: Shri Rajeev Ranjan Prasad
(rajeevphy@igcar.gov.in)

Course Details:

- **NUCLEAR THEORY BASICS**

  - Properties of Nuclei: Size, shape and density of the nucleus, nuclear forces, nuclear structure, binding energy, stability of nucleus, radioactivity
  - Fission Process: Spontaneous and induced fission, liquid drop model, fission neutrons, delayed neutrons, fission gammas, fission products, fission product yield, FP mass asymmetry, formation and removal of FPs in a reactor
  - Concept of Nuclear Reactor: Fission energy, fission rate and reactor power, energy balance, fissile, fertile and fissionable materials, reactor materials: fuel, coolant, structure, control and shield, fission product activity after shutdown – decay heat, types of reactors
  - Interaction of Neutrons with Matter :Production of neutrons, elastic and inelastic scattering, radiative capture and their significance in reactors, production of photo neutrons, transmutation
  - Concept Cross-section :Microscopic and macroscopic cross-section, mean free path, Maxwell-Boltzmann distribution and its departure, structural changes caused by neutron reactions
  - Variation of Cross-section with Energy: Fast, resonance and thermal ranges, 1/v law of neutron cross-section, resonance absorption, Breit-Wigner formula, Doppler effect Capture to fission ratio, Eta vs E curve, conversion and breeding concepts, Thorium utilization

- **BASIC REACTOR PHYSICS-STATIC**

  - Diffusion of Neutrons: Fick's law and its validity, steady state neutron diffusion equation, concepts of neutron flux and current, interface conditions, diffusion coefficient, diffusion length and extrapolation distance
  - Chain Reaction :Four factor formula, conceptual treatment of diffusion of one group of neutrons in non multiplying and multiplying media, infinite and effective multiplication factors, bare homogeneous reactor concepts, material and geometrical buckling, sub criticality and super criticality, critical mass, non leakage probabilities in bare homogeneous cores, neutron cycle and life time in finite reactor
  - Slowing Down Process: Neutron Slowing down, slowing down power and moderating ratio of moderators, slowing down with spatial migration, Fermi age concepts, migration length, multi zone reactors, ideas of reflectors/blankets, reflector savings, form factor

- **TIME DEPENDENCE**

  - Reactor Kinetics: Time dependent neutron diffusion equation, one group kinetic equation, role of delayed neutrons, prompt neutron life time, point kinetic model to illustrate importance of delayed neutrons, reactor period, reactivity and its units
  - Core Burnup and Neutron Poisons: Burnup equations including fission products, Xenon and Samarium poisons, Xenon loads (operating and post shut down), variation of Xenon load with power and enrichment, Xenon oscillations and their control

- Reactivity Coefficients and Reactor Experiments: Temperature and void coefficients of reactivity, their relevance to reactor safety Techniques to control reactors, typical reactivity balance, long term burnup, fuel management, reactor control system – requirements of physics aspects, reactor shutdown mechanisms and neutron monitoring during operation and shut down Approach to criticality, physics measurements and calibrations/validations

- **FAST BREEDER REACTORS**

- Introduction: Fast reactors as breeders, comparison of fast and thermal reactors, types of fast reactor, role of fast reactors in Indian nuclear power program
- FBR Neutronics: Neutron spectrum, reaction cross-section, core characteristics, blanket characteristics, breeding potential, breeding ratio and breeding gain, doubling time, Multigroup diffusion theory methods and summary of steady state experimentals for FBR Effective delayed neutron fraction and prompt neutron life time, fuel expansion and bowing, sodium void reactivity effect, Doppler reactivity effect, long term reactivity effect - in FBR
- FBR Core Design: General features of FBR core, specific power, linear rating, burnup, fluence, requirement and choice of core materials (fuel, coolant and structural materials), test reactors, commercial fast reactors, pin diameter, core height/diameter ratio, blanket thickness
- Salient physics aspects of FBTR and PFBR
- Reactor Shielding: Source of various neutron & Gamma radiation within the reactor system; Attenuation of neutrons & gamma rays; Dose rates for gamma rays for various source geometries; Buildup factors for homogeneous & multiple layer shields; Removal diffusion theory for neutron attenuation; coolant activation, heat generation. Streaming of radiation through gaps & void in the shield; description of various shielding arrangements of Indian reactors

Course Outcomes:

This course develops comprehensive knowledge of nuclear theory, neutron interactions, reactor statics and kinetics, burnup, reactivity coefficients and fast breeder reactor physics. Students gain the ability to analyze FBR core characteristics, breeding performance, safety-related reactivity effects and reactor shielding against neutron and gamma radiation.

References:

1. S. Glasstone and S. Sesonske, Nuclear Reactor Engineering, Van Nostrand, 1963.
2. S. Glasstone and M.C. Edlund, Elements of Nuclear Reactor Theory, Van Nostrand, 1952.
3. J. R. Lamarsh, Introduction to Nuclear Engineering, Addision Wesley, NY, 1960.
4. M. El-Wakil, Nuclear Power Engineering, McGraw-Hill
5. P.P. Zweifel, Reactor Physics, McGraw-Hill, 1973.
6. Weston M. Stacy, Nuclear Reactor Physics, John Wiley & Sons, Inc. 7. A.E. Walter & A.B. Reynolds, Fast Breeder Reactors, Pergamon Press.

HP: Health Physics & Radiological Safety (25 Lecture Hrs)

Coordinators: Dr. S. Chandrasekaran
(schand@igcar.gov.in)

Course Details:

- Introduction: Radiation sources: Natural and Induced radioactive sources, units of radioactivity, half-life and decay constant, specific activity. Basic interaction mechanism of a) alpha b) Beta c) Gamma/X-rays d) Neutrons with matter. Definition of various dosimetric terms (exposure, absorbed/equivalent/effective dose, concept of radiation/tissue weighting factors and their importance (SI units & new units). Concepts of Exposure measurement: Free air and Air wall chambers, Exposure-dose relationship, Bragg-Gray principle.
- Biological effects of Radiation: Human body: Cells, tissues and organs, structure of cell, cellular effects. Factors, which influence the damage of cell. Interaction of radiation with biological matter. Radiation effects: stochastic and deterministic. Acute and delayed effects. Types of exposure (natural, occupational, medical and public).
- Radiation Protection and Regulations:
  - Importance of radiation protection program in DAE, Atomic Energy act, National and International regulatory bodies, their role and responsibilities., Radiation Protection Rules, Dose limits stipulated by these bodies. Dose limits observed in India.
  - Radiation protection philosophy, Principles of radiation protection, concept of ALI & DAC (with suitable problems). Fundamentals of ICRP respiratory model, entry through ingestion, GI track model.
  - Principles of radiation detection and monitoring: Basic operating principles of a) Gas b) Scintillation (including thermo luminescence detectors) and c) Semiconductors detectors.
  - Type of Radiation monitors/Radioactivity measurement methods adopted for radiation protection.
- Radiation protection and measurement (External and Internal):
  - Control of external exposures (with problems in each case).
  - Buildup concept, shielding from alpha, beta, gamma and neutron sources. Shielding from mixed sources.
  - Routes of intake of radioactive material,
  - Radiotoxicity and classification of laboratories, design of laboratory for radioactive work, Radioactive waste classification and management. Personal monitoring, area-monitoring, air monitoring. Bioassay, whole body counting techniques. Use of personal dosimeters (TLDs, pocket dosimeters)
- Radiation Protection procedures: Procedures followed in radiation work places, work permits, zoning concept, contamination control methods, and rubber areas, spill pack (gloves + absorbing paper), Decontamination techniques. Precautions during radioactive source storage and handling, safety during transportation. Nature of duties and responsibilities of Radiation Safety Officer/Health Physicist.
- Nuclear Accidents, Emergency Preparedness and Management: Reasons for accidents, classifications of accidents, International Nuclear Events Scale. Types of emergency, emergency preparedness.
- Radiological aspects and Environmental Impact of FBRs: Radiological aspects of Fuel Cycle Facilities
- Industrial Safety Aspects: Introduction to Industrial Safety (accident prevention technique, Job safety analysis, control measures), Factories Act, 1948 & Atomic Energy Factories Rules, 1996,ndustrial safety aspects (Physical and Chemical Hazards),Industrial safety aspects (safety in Machineries, hand tools & Material handling equipments, personal protective equipments, etc)Construction safety (includes Electrical Safety & Work Permit System)

Course Outcomes:

This course provides in-depth understanding of radiation sources, interaction with matter, biological effects and dosimetry. It builds competence in radiation protection principles, monitoring and measurement techniques, regulatory requirements, waste management, emergency preparedness and industrial safety, with specific emphasis on fast reactor and fuel cycle facilities.

References:

13. Introduction to Health Physics – Herman Cember
14. Introduction to Radiation Protection – Alan Martin
15. IAEA Regional Basic Professional Training Course on Radiation Protection (Course jointly organized by BARC and IAEA), October 26-Dember 18, 1998
16. Nuclear Radiation Detection - W.J. Price
17. Radiation Detection and Measurement - G.F. Knoll
18. Biological Effects of Radiation – J.E. Coggle
19. Nuclear Radiation Detectors by S.S. Kapoor and V.S. Ramamurthy (Publication: New Delhi, Wiley Eastern Ltd, 1986)
20. Atoms, Radiation and Radiation Protection by James E. Turner 1986
21. Problems and solutions in Radiation Protection by James E. Turner, 1988
22. Guide Lines for Hazard Evaluation Procedures – American Institute of Chemical Engineers
23. Risk Analysis in the Process Industries: The Institute of Chemical Engineers, England.
24. Loss Prevention in The Process Industries: Hazard Identification, Assessment and Control; Vol-1, 1996 2 Edition, Frank P Lees.

NR: Nuclear Reactors (50 Lecture Hrs)

Coordinators: Shri D. Nagasivayya
(dnsiva@igcar.gov.in)

Course Details:

- **Mechanical Aspects of Power Plant Engineering:**

Basic thermal Cycle used in NPS, means of Improving cycle efficiency, Major components in thermal and Nuclear stations, Heat Balance typical calculations, Details of equipment – Steam Generators, Turbines, Condensers, Feed Water heaters, De-aerator feed pumps, condensate and other pumps: condenser cooling water system: C&I; steam pressure control, steam discharge and steam dumping features.

- **Thermal Power Reactors :**

Layout of Nuclear Power Plant; Zoning requirements: layout of typical PHWR; description of layout in the reactor building; Special requirements for'; nuclear components regarding material selection, reliable operation with examples of pumps, valves, heat exchangers etc. operating environment (including capabilities to withstand seismic loads). Description of calandria, end shield and coolant channel (including fitting). Description of reactivity control scheme and related hardware e.g. zone control, regulating rods, absorbers, shutdown systems etc. Fuel and Fuel transfer system; Primary Heat Transport System; emergency core cooling system; Moderator system; Auxiliary System; Description of process Water, Fire Water and Ventilation system (emphasis on role played as safety support systems); Containment and associated safety systems to mitigate consequences of accidents and contain reactivity release; ultimate heat sink and heat removal paths.A brief overview of PWR, BWR and AHWR

- **Fast Power Reactors :**
  - Fast Reactor Physics and Safety: Role of FBR’s, breeding ratio, doubling time, core design features - Static and Dynamic, control rod design, shielding principles, Fuel management, safety.
  - Overview of FBR: FBTR and PFBR. Comparison of FBRs: Core & important design parameters, comparison of core components, major primary and secondary system components.
  - Core Engineering: Description, choice of core materials, Engineering design of core, High temperature design methods.
  - Heat Transport Systems: Introduction, Design of IHX, SG, sodium pump, sodium piping, Decay heat removal system.
  - Instrumentation & Control: FBR instrumentation requirements, Neutronic Instrumentation and failed fuel detection methods, Reactor protection instrumentation and process instrumentation.

- **Sodium Technology**
  - Properties of Sodium: Physical and chemical properties, (Hazardous nature and sodium-air, sodium-water reactions), heat transfer properties, Manufacture of sodium, Heat transfer in liquid metals, Hartman effect in liquid metals

- Sodium Systems – General Description: Components of a sodium system, process, cover gas system etc.
- Impurities in Sodium, Purification Methods: Impurities in sodium, purification methods, impurity monitors, (plugging indicator, on-line hydrogen, oxygen and carbon monitors)
- Sodium System: Components, piping and Quality Control Materials, design aspects, tanks, valves, vapor traps and other mechanical engineering aspects, sodium centrifugal pumps, high temperature piping for sodium, fabrication aspects, quality control
- Sodium Pumps and flow meter: Electromagnetic pumps and flow meter for sodium systems
- Electrical Systems for Sodium Loops: Electrical supply, heating systems, heater control, types of power supply

- Instrumentation and Control: Level, leak, flow and temperature monitoring, pressure measurement, control of process parameter in sodium systems, under sodium viewing.
- System Operation Aspects: Sodium system pre-commissioning checks, methods of checking all components, limiting conditions of operation, surveillance checks etc.
- Sodium component cleaning, fire and safety
- Sodium removal and disposal methods, sodium fire and extinguishment methods, system and industrial safety aspects.

Course Outcomes:

This course imparts integrated knowledge of thermal and fast nuclear power reactors, covering plant engineering, reactor systems, heat transport, instrumentation, control and sodium technology. Students develop the ability to understand design, operation, safety systems and comparative features of PHWRs, PWRs, BWRs and fast breeder reactors.

References:

11. Nuclear Power Engineering, M. EI-Wakil, Mcgraw Hill Book Co., New York.
12. Steam Power Station, G.A. Gassort.
13. Power Plant Engineering & Economics, Strosal & Vapet.
14. Central Electricity Generating Board (London), Modern Power Station Practice, Nuclear Power Generation Ed 2, Oxford, Pergamon, 1971.
15. Weisman. J. Modern Power Plant Engineering, Englewood Cliffs, Prentice Hall, 1985.
16. IAEA Directory of Nuclear Reactors, Vol. IV, Power Reactors, Vienna.
17. Fast Reactor Technology: Plant Design, J. G. Yevick, M.I.T. Press.
18. Fast Breeder Reactors, A.E. Waltor & A.B. Reynolds, Permagon Press.
19. Status of liquid metal cooled fast reactor technology, IAEA-TECDOC—1083
20. Material for Sodium Technology portion will be provided during the course

RE: Reactor Engineering (40 Lecture Hrs)

Coordinators: Shri Sriramachandra Aithal
(saithal@igcar.gov.in)

Course Details:

- **Core design**
  - Introduction - Role of FBR, Main Characteristics of LMFBR, Sodium as coolant, Core Configuration, Definition of NSSS & BOP, Pool & Loop Type Design.
  - Fixing Size & Parameters of LMFBR - Test Reactor, Commercial & Prototype Reactor, Unit energy cost, Hot Spot temperature of Clad, Optimisation on Pin Diameter.
  - Definition of Smear Density, DPA & Burn up.
  - Fast Reactor Core – Fuel, Basic Requirements, Choice of fuel material, Candidates for Fuel, Swelling, Fabrication cost, Reprocessing, Negative Doppler coefficient, Thermal expansion, Burnup.
  - Absorber – required features, candidate materials
  - Structural Material in Core - Requirements of Core Structural Material, Effect of Neutron Irradiation on SS, Radiation Hardening, Embrittlement, Void Swelling, Irradiation Creep, Effect of Swelling & irradiation induced creep, Efforts to reduce swelling.
  - Sub-Assembly (SA) Design - Basis for Number of pins in a fuel SA, Pin spacers, Gas Plenum, Duct considerations, Volume Fraction, Assembly Length.
  - Other Subassembly design - Blanket, CSR, DSR, Reflector, Inner B4C, Outer B4C and Steel Shielding subassemblies.
  - Thermal Design of Fuel Pin - Thermal Analysis, Causes for fuel restructuring, Developing Analytical Model, Necessary physical parameters, Na Heat Transfer coefficient, Hot spot Analysis, Calculation of temperature distribution across fuel pin.
  - Mechanical Design of Fuel Pin - Failure Criteria for Pin, Strain Limit Approach, Cumulative Damage Fraction, Stress analysis, Cladding wastage.
  - Hydraulic Design of Core - Factors to be reviewed for Core Hydraulic Design - Hydraulic lifting force, Mixing studies, Power flattening & flow zoning, Vibration.
  - Handling of core subassemblies - Inherent problems associated with on-line fuel handling, Fresh SA Handling, Spent SA Handling.

- **Coolant circuits**
  - Selection of coolant for FBRs, thermal, transport, nuclear, chemical and other considerations. comparison between various coolants. Special characteristics of sodium. Its impact on heat transfer and structural mechanics considerations. Selection of structural materials, basis and important alloying elements.
  - Main heat transport system: primary and secondary sodium system, necessity of intermediate loop. Safety Grade decay Heat removal system, Decay heat, necessity for independent system.
  - Features of major components such as intermediate heat exchangers, steam generators, sodium to air exchangers, sodium pumps, electro magnetic pumps, sodium tanks, support design for sodium components from thermo mechanical and seismic considerations, sodium valves and types.
  - Design criteria, Loadings to be considered, Analysis method and validation methodology.
  - Special characteristic of sodium piping, sodium leak, sodium fire, various types of leak detectors, continuous and discontinuous level detectors etc.
  - Sodium purification loop, oxygen control, plugging indicator, cold trap, characteristics

and features.

- Operating experiences of fast reactors, failures and sodium leaks reported for Phenix, Monju, PFR and other fast reactors, reasons for leak and remedy.

Course Outcomes:

This course develops advanced understanding of fast reactor core engineering and coolant circuit design, including fuel pin, subassembly, thermal–hydraulic, mechanical and structural design aspects. Students gain the ability to analyze sodium-cooled system components, safety-grade heat transport systems, material behavior under irradiation and operational experiences of fast reactors.

References:

1. Fast Breeder Reactors - Walter, A.E. & Reynolds, A.B., PERGAMON Press.
2. Fast Reactor Technology - Plant Design - Yevick, J.G., M.I.T. Press.
3. Fundamental Aspects of Nuclear Reactor Fuel Elements - Donald R. Olander, U.S.Department of Energy, 1985.

CORE COURSES

ME1: Code Design for Pressure Vessels & Piping (30 Lecture Hrs)

Coordinators: Shri S. D. Sajish
(sajish@igcar.gov.in)

Course Details:

- Membrane theory for thin shells, stresses in cylindrical, spherical and conical shells, dilation of above shells, general theory of membrane stresses in vessel under internal pressure and its application to ellipsoidal and torispherical end closures.

- Thick cylinder and sphere and derivation of Lame's equations. Derivation of ASME Sec. VIII Div. 1 & Div -2 equations for cylindrical spherical and conical shells, ellipsoidal and torispherical end closures.

- Bending of circular plates and determination of stresses in simply supported and clamped circular plate. Basis of ASME equation for flat closures.

- Openings, nozzles and external loading. Stress concentration in plate having circular hole due to bi-axial loading. Theory of reinforced opening and reinforcement limits.

- Beam on elastic foundation and its application to thin-walled pressure vessels. Extent and significance of load deformation on pressure vessel. Reinforcement rules for ASME, Sec. VIII Div.1. Local Stresses in shells due to external loadings from nozzles and lugs etc.

- Bolted Flanged joints. Types of flange joints. Types of gasket and their selection. Bolting design. Flange loads and moments. Design of flange as per ASME Boiler and Pressure Vessel and B 31.3 Code.

- Supports for vertical and horizontal vessels. Design of base plate and support lugs. Types of anchor bolt, its material and allowable stresses. Design of saddle supports.

- Buckling of vessels under external pressure. Elastic buckling of long cylinders, buckling modes, Buckling (collapse) coefficients. ASME procedure for design of vessels under external pressure. Design for stiffening rings. Design of shells for axial compression.

- Derivation of TEMA Design equation for tube sheets. Background of the ASME design rules for tube sheets.

- Piping thickness as per ANSI ASME B31.1 and B31.3 piping code. Flexibility factor and stress intensification factor. Design of piping system as per B31.1 piping code. Design of piping for hazardous fluid as per B31.3

- Design consideration for pressure vessel. Design pressure and temperature, Allowable stresses, Impact toughness requirement as per ASME Sec. VIII Div.1 code. Non-destructive examination of welds as per ASME Sec.VIII, Div.1 code. Difference between Sec. VIII Div.1 & Div.2.

Course Outcomes:

This course develops the ability to design pressure vessels and piping systems using membrane theory, thick cylinder theory, plate bending and buckling concepts. Students gain proficiency in applying ASME Section VIII (Div. 1 & 2), ASME B31.1 and B31.3 codes for design of shells, heads, nozzles, flanges, supports and piping under internal and external loads.

References:

1. Harvey J F , ‘Pressure vessel design’ CBS publication.
2. Brownell. L. E & Young. E. D , ‘Process equipment design’, Wiley Eastern Ltd., India.
3. ASME Pressure Vessel and Boiler code, Section VIII Div 1 & 2, 2003.
4. American standard code for pressure piping , B 31.1.
5. Standards of Tubular Exchanger Manufacturers Association, Eighth Edition ,1998.

ME8: Finite Element Method (30 Lecture Hrs)

Coordinator: Shri S. D. Sajish
(sajish@igcar.gov.in)

Course Details:

- Introduction to FEM as applied to solid mechanics. Energy principles in structural mechanics and principles of minimum potential energy.
- Element Shape and Shape Functions: Generalised co-ordinates. General requirements of shape functions; Lagrangian and Hermitian interpolation functions – CO, C1 continuity; Natural coordinate system; Derivation of shape functions for Bar, Beam, Plane, Brick and Plate elements.
- Bar Element: Derivation of elemental stiffness matrix and load vector; Transformation from element to global coordinate system; Assembly of Global stiffness matrix and load vector; Solution of typical 2D-plane Truss problems to evaluate Displacements and Member forces/stress; Thermal stress evaluation in Bars/Truss.
- Beam Element: Derivation of elemental stiffness matrix and load vector; Solution of simple Beam problems to evaluate Deflections/rotations; BM/SF distribution and determination of stresses, Shear deformation in beams. Curved Beam Element: Derivation of elemental stiffness matrix and load vector; Derivation of stiffness matrix for elbow.
- Axisymmetric Thin Shell Element: Strain-displacement and stress-strain relationship; Derivation of stiffness matrix and load vector for 2 noded axisymmetric thin shell element. 2D Plane Elements – 3 Noded Triangular Element: Derivation of elemental stiffness matrix and load vector, Plane Stress/Plane Strain & Axisymmetric elements: Evaluation of Strain/Stress.
- 2D Isoparametric Element – 4, 8 and 12 noded quadrilateral Element: mapping of parent element to global space; Jacobian matrix; necessary and sufficient conditions for existence of inverse of Jacobian; Derivation of stiffness matrix for plane & axisymmetric elements; Evaluation of strain/stress at Gauss points.
- Introduction and Application of 3D Elements: Strain displacement and stress-strain relationship; Tetrahedron, Triangular prism and Hexahedron elements.
- Plane Bending Elements: Thin and Thick plate theory; Elements based on Kirchoff's Theory; Elements based on Mindlin Theory; Shear locking and Reduced Integration.
- Shell Element: Strain-displacement and stress-strain relationship; Flat plate and curved shell elements; 4 and 8 noded degenerated thick shell Elements, basic assumptions, degree of freedom, shape functions and shear locking.
- Incompatible Displacement Model: Bending deficiency in the linear strain quadrilateral element; Incompatible quadrilateral element.
- Introduction to Nonlinear Problems. Meshing and Errors: Finite Element Modeling and Discritization Criterion, Adaptive meshing, classification of FEM stresses per ASME code, sources of potential error in the finite element solution.

Course Outcomes:

This course provides comprehensive understanding of finite element formulation for bars, beams, plates, shells and 3D solids based on energy principles and variational methods. Students develop skills to model, discretize and analyze linear and nonlinear structural problems, evaluate stresses and errors, and interpret results in accordance with ASME stress classification concepts.

References:

1. Finite Element Procedures-K.J.Bathe, Prentice Hall, 1996.
2. Concepts and Applications of Finite Element Analysis, R.D.Cook,D.S.Malkus & M.E.Plesha, 4th Ed., Prentice-Hall India, 2003.
3. An introduction to the Finite Element Method-J.N.Reddy, 2nd Ed., McGraw Hill Education (ISE editions)-1993.
4. Finite Element Method-O.C.Zienkiewicz & R.L.Taylor, 5th Ed., Vol.1, Butterworths-Heinemann,2000.
5. Finite Element Method-O.C.Zienkiewicz & R.L.Taylor, 5th Ed., Vol.2, Butterworths-Heinemann,2000.
6. The Finite Element Methods: its basics and fundamentals- O.C.Zienkiewicz ,R.L.Taylor &J.Z.Hu, Elsevier,2005.
7. The Finite Element Method: Linear,Static and Dynamic Finite Element analysis-T.J.R.Hughes, Dover Publication,2000.
8. Fundamentals Finite Element Analysis and Applications-M.Ashghar Bhatti, John-Wiley & Sons, NJ,2005.

ME10: Advanced Heat and Mass Transfer (30 Lecture Hrs)

Coordinator: Shri Rajendra Kumar
(mrk@igcar.gov.in)

Course Details:

- Basic equations: Kinematics of fluid flow. Streamline, streakline and pathline; stream function, vorticity & deformation of a fluid element. Basic equations governing heat conduction, fluid flow & mass transfer (viz. the continuity', momentum and energy' equations) with special reference to Navier-Stokes & Bemoulli equations.
- Laminar Boundary Layer and Forced Convective Heat: Formulation of differential equation for hydrodynamic and thermal boundary layer. Different analytical method of reduction of boundary layer equations and theoretical formulation of boundary layer thickness. Study of jets and inlet flow and flow separation in the light of Boundary Layer Theory. Convective heat transfer for intemal and extemal flows. Low and high Prandtl number limits and different thermal boundary conditions Numerical Solution of Reduced Boundary Layer Equations: BVP, Keller box method.
- Turbulent Flow and Heat Transfer: Reynolds decomposition for turbulence. Prandtl's mixing length theory, Mixing length models. Structure of turbulent boundary layer over flat plate and through circular cylinder. Calculation of friction factor and drag coefficient. Analytical and semi-analytical. correlations for calculating heat transfer coefficients. Analogy between heat and momentum transfer. Reynolds analogy, von Karman-Prandtl analogy, Martenelli analogy, Lyons analogy.
- Turbulence Modeling: Eddy diffusivity models: k-£ and k-w) models, RNG based k- £ model. Reynolds stress models: algebraic & differential models. Low Reynolds number models Large eddy simulation: Smagorinsky and Dynamic sub-grid scale models
- Natural Convection: Basic Equations of natural convection. Boussinesq approximation. Derivation of Dimensionless groups from basic equations. Analytical approximations
- Principles of heat transfer in porous media: Single phase flow in porous medium Darcy Moment, porosity, permeability etc.., homogenization method, continuity equation & energy equation, introduction to 2 phase flows & heat transfer in fluid flows.
- Heat Transfer With Phase Change : Introduction of two phase flow and basic relations; flow regimes in adiabatic and diabatic vertical co-current flow and in adiabatic co-current horizontal flows. Basic equations of two phase flow; Homogenous & separated flow models for two phase flow, void fraction & phase velocity ratio (Zivi's model). Introduction to boiling heat transfer and bubble nucleation; Regimes in boiling heat transfer (a) pool boiling (b) flow boiling: Heat transfer correlation for pool boiling (Rohsenow's correlation) and flow boiling (Chen's correlation). Condensation heat transfer: Nusselt's theory and its limitations: Jet condensation fundamentals and its application in containment cooling. Critical heat flux: Various models of critical heat flux, CHFR, MCHFR Critical power concept. Post dryout heat transfer. Various models available for calculation of heat transfer coefficient.. Critical Flow. Models for single - phase and two-phase critical flow.
- Radiation heat transfer: Radiation heat transfer. Introduction; Reflection, absorption, transmission and emission; concept of black and grey body; total emissive power and Stefan-Boltzmann constant. Kirchoffs law. Radiation heat transfer between two bodies: shape factor & law of reciprocity; radiation heat transfer between two grey bodies.

Course Outcomes:

This course equips students with advanced knowledge of laminar and turbulent convection, boundary layer theory, natural convection, porous media and phase-change heat transfer. Learners gain the ability to analyze boiling, condensation, critical heat flux, radiation heat transfer and turbulence models, with application to nuclear and high-temperature thermal systems.

References:

1. Fox. J. A, Introduction to Engineering Fluid Mechanics, New York, Mc Graw Hill, 1974.
2. Frank M White, Fluid Mechanics, 5th Edition, Boca Raton, CRC Press, 2000.
3. Cengel Y.A, Introduction to Thermodynamics and Heat Transfer, New York, Mc Graw Hill, 1997.
4. Frank P. Incropera, David P. DeWitt, Fundamentals of Heat and Mass Transfer, 5th Edition, New York, John Wiley & Sons, 1996
5. Adrian Bejan, Convection Heat Transfer, New York, John Wiley & Sons, 2004.
6. Wilcox. D.C, Turbulence Modeling for CFD, California, Dcw Industries, 1993.
7. Pope S.B, Turbulent Flows, Cambridge, Cambridge University Press, 2000.
8. Stephan K, Heat Transfer In Condensation Boiling, Berlin, Springer Verlag, 1992.
9. Tong. L.S, Boiling Heat Transfer And Two Phase Flow, New York, John Wiley & Sons, 1966.
10. P.B. Whalley, Two-Phase Flow and Heat Transfer, Oxford Press, 2005.
11. Hetsroni G, Handbook of Multiphase Systems, Washington, Hemisphere, 1982.
12. Hewitt. G.F, Process Heat Transfer, Boca Raton, CRC Press, 1994.
13. Collier. J.G, Convective Boiling and Condensation, London, Mc Graw Hill, 1972.

ME6: Computational Fluid Dynamics (30 Lecture Hrs)

Coordinator: Shri Rajendra Kumar
(mrk@igcar.gov.in)

Course Details:

- **Basics of Fluid Flow, Heat Transfer and Numerical Analysis:**
    - Kinematics of fluid flow. Streamline, streakline and pathline; streamfunction, vorticity and deformation of a fluid element.
    - Basic equations governing heat conduction, fluid flow and mass transfer (viz. the continuity', momentum and energy' equations) with special reference to Navier-Stokes and Bemoulli equations.
    - Classification of Partial Differential Equations (PDEs).
    - Discretization of conduction equation with Dirichlet, Neumann and periodic boundary conditions, by ADI and TDMA methods.
    - Temporal integration: explicit, implicit scheme.
    - Discretization of convection, upwinding, Streamline-Upwind Petrev Galerkin method.
    - Discretization of convection-diffusion problem: exponential scheme, power-law scheme

- **Numerical Solution of Complete Fluid Flow and Energy Equation:**
    - Formulations of governing equations used in numerical simulation:
    - Stream function-temperature formulation.
    - Stream function-vorticity-temperature formulation.
    - Velocity-vorticity-temperature formulation: Poission, Cauchy-Riemaim and Biot-Savart form.
    - Primitive-Variable (P-V-T) formulation.
    - Pressure velocity coupling for incompressible flow.
    - Staggered, Non-Staggered Grid (momentum interpolation, pressure-weighted interpolation).
    - Discussion on MAC, PISO, SIMPLE and SIMPLEN family of Methods.
    - Simple grid generation techniques for structured grid:
    - Elliptic. parabolic and hyperbolic equation method.
    - Grid adaptation.
    - Domain decompositions in CFD and heat transfer.
    - SIP and preconditioned conjugate gradient methods for solution.
    - Numerical Solution of Reduced Boundary Layer Equations: BVP, Keller box method for laminar and forced convective boundary layer problems.
    - Numerical solution of approximate equations for natural convective heat transfer problems including porous medium.
    - Mathematical formulation and numerical solution of compressible flows and heat transfer.

Course Outcomes:

This course develops strong foundations in numerical modeling of fluid flow and heat transfer using finite volume discretization, pressure–velocity coupling and turbulence modeling techniques. Students gain competence in solving Navier–Stokes and energy equations, grid generation, boundary layer simulation and analysis of incompressible and compressible flows.

References:

1. An Introduction to Computational Fluid Dynamics: The Finite Volume Method - H.K. Versteeg and W. Malalasekera, Addison-Wesley Longman, Limited, 1995, Reprinted in 1996.
2. Numerical Heat Transfer and Fluid Flow - S.V. Patankar, McGraw-Hill, 1981.
3. Computational Fluid Flow and Heat Transfer – K.Muralidhar, T.Sundararajan, Narosa Publishing - New Delhi, 2003 (IIT Kanpur series of advanced texts).
4. Heat Transfer- J.P.Holman, 9th Ed., McGraw Hill, NY.
5. Convective boiling and condensation- J.G.Collier, McGraw Hill, London,1972.

ME13: Reliability Engineering (20 Lecture Hrs)

Coordinator: Dr. M. Ramakrishnan
(mramki@igcar.gov.in)

Course Details:

- Reliability Mathematics- Fundamentals of probability, Random Variables and their probability distributions, common distribution functions, Uniform, Normal, Lognormal, Exponential and Extreme value distribution, correlations, Regression analysis, Bayesian Methods, Functions of Random Variables, Central Limit theorem
- Elements of Component Reliability – Definition of reliability, Availability and risk, Basic Component reliability model, Failure rate & hazard rate, Life testing, Component reliability.
- Reliability in Engineering Design – Limit state, Probability of failure, Monte Carlo simulation method, Generation of Uniform Random Number, Generation of Normal Random Number, General procedure of generating random numbers from an arbitrary distribution, Accuracy of probability estimates, Reliability Index, First Order Second Moment Reliability estimates, Reliability Index, First Order Second Moment Reliability Index, Hasofer Lind Reliability Index, Rackwitz Fiessler procedure, Correlated random variables.
- Probabilistic Fracture Mechanics – Brief overview of failure modes for flawed structures, linear elastic fracture mechanics, net section collapse, R6 method, fatigue analysis, crack growth analysis, Application of PFM to nuclear structural components.
- System Reliability Analysis – Elements and systems, series and parallel systems, Reliability bounds on structural systems, Failure mode and Effect analysis, Reliability block diagram, Redundancy techniques in system design, Fault tree and Event tree analysis, Reliability and availability of repairable systems.
- Application of Reliability – PSA of Nuclear Plants, Identification of initiating event, Event sequence modeling, system modeling, input data analysis including common cause failure and human reliability data quantification, determination of Core Damage. Frequency and its significance. Internal and External events, Reliability centered maintenance, Risk based in-service inspection strategies, Important measures, Risk based ranking matrix.

Course Outcomes:

This course imparts the principles of probability theory, component and system reliability, probabilistic fracture mechanics and reliability-based design. Students develop the ability to perform fault tree and event tree analysis, Monte Carlo simulation, PSA of nuclear plants, and apply risk-informed maintenance and inspection strategies.

References:

1. Reliability and Maintainability Engineering, Charles.E.Ebeling, Tata- McGraw Hill, 2000.
2. Fracture Mechanics- Fundamentals and Applications, T.L.Anderson , CRC Press, 2005.
3. Lecture Notes-Topics in Solid Mechanics-Reliability Analysis and Design, Sharit Rehman, 1999.
4. Structural reliability analysis and prediction-R.E.Melchers, Ellis Horwood Limited, 1987.
5. Probablistic Safety Assessment in Chemical and Nuclear Industry-R.R.Fullwood, BH, Oxford, 2000.
6. Probability, reliability and statistical methods in engineering design – Halder. A and Mahadevan.S., 2000, John Wiley & Sons, Newyork.
7. Introduction to reliability engineering - E.E. Lewi, John Wiley, NY, 1987
8. An introduction to reliability and maintainability engineering, Tata-Mcgraw hill, New Delhi 2000.
9. Probabilistic structural mechanics handbook – C(Raj) Sundararajn, 1995, Chapman and Hall, NY

ME14: Manufacturing Technology (40 Lecture Hrs)

Coordinator: Dr. M. Vasudevan
(dev@igcar.gov.in)

Course Details:

- **Curriculum for Metal Forming**
  - **Uniaxial tensile test:**
    - Engineering stress, engineering stain, true stress, true strain;
    - Extraction of plastic stress-plastic strain data from load – elongation data of uniaxial tensile tests; Hollomon type and Voce type constitutive relations;
    - Tensile instability and significance of strain harkening exponent;
    - Determination of strain rate sensitivity index and the significance of strain rate sensitivity;
  - Stress matrix and the derivation of the Cauchy relation from the law of conservation of linear momentum; concept of principal stress;
  - Small strain matrix and rotation matrix obtained from the displacement functions;
  - **Elements of the theory of plasticity:**
    - Decomposition of stress matrix to hydrostatic and deviatoric matrices;
    - Yield surfaces as a function of the second and third invariants of the deviatoric matrix with von Mises and Tresca criteria being examples; concept of equivalent stess;
    - Normality flow rule and convexity of the yield surface; concept of equivalent strain

- **Curriculum for Materials Joining**
  - **Welding Processes**
    - Fusion Welding Processes: Arc Welding Processes like SMAW, GTAW, GMSE, GVSE etc. and Beam welding process like EB welding and Laser Welding
    - Solid state Welding Process like Friction Welding, Friction Stir Welding, Diffusion bonding, Explosive welding
    - Resistance Welding Processes
  - **Thermal Cycle during welding**
    - Weld Thermal Cycle, Dependence of bead shape with welding speed, prediction of weld thermal cycle
  - **Residual Stress and Distortion**
    - Generation of residual stress, Effect of residual stress on performance, removal of residual stresses, measurement of residual stresses
    - Origin of Distortion, Control of distortion

Course Outcomes:

This course provides in-depth understanding of metal forming mechanics and materials joining technologies, including plasticity theory, constitutive relations, yield criteria and strain hardening behavior. Students gain competence in welding processes, weld thermal cycles, residual stresses and distortion control, relevant to structural and nuclear engineering applications.

ME4: High Temperature Design & Inelastic Analysis (25 Lecture Hrs)

Coordinator: Shri S. D. Sajish
(sajish@igcar.gov.in)

Course Details:

- Introduction: Modes of failure, material selection, criteria to assess creep effect, creep law, creep-fatigue interaction, thermal striping
- Design Practice: Loading category, primary, secondary and peak stress intensity, allowable stress intensity (Sm), assessment of basic wall thickness, strain limits
- Analysis: strain range under multi axial state of stress, Nuber's rule, triaxiality, elastic followup, fatigue damage, allowable numbers of cycle, creep damage, creep life prediction, creep rupture strength, creep fatigue interaction, ratcheting, efficiency diagrams and creep buckling
- Fracture mechanics, creep crack growth, introduction to RCC-MR A16
- In elastic Analysis: General principles for constitutive models, non unified model (plastic + creep), flow rule, creep strain hardening, classified models, viscoplastic material model, non-linear kinematic hardening, isotropic hardening, plastic strain memory, finite element Implementation, automatic time integration

Course Outcomes:

This course enables understanding of high-temperature failure modes, including creep, creep–fatigue interaction, ratcheting, thermal striping and creep buckling. Students develop capability to perform elastic and inelastic analysis using constitutive models, apply ASME Section III Subsection NH and RCC-MR A16, and predict creep life, creep rupture strength and crack growth using analytical and finite element methods.

References:

1. Creep Analysis – H.Krauss
2. Mechanical Metallurgy-G.E. Dieter
3. Creep in Structures-A.R.S.Ponder and Drkhayhurst
4. Advances in Creep Design-Ed.A.I.Smith and A.M.Nickelson
5. ASME Section3 Subsection NH-1
6. French Design Code-RCCMR-Subsection RB

ELECTIVE COURSES

ME3: Structural Integrity Assessment Methods and NDE (30 Lecture Hrs)

Coordinator: Shri Rajeev Ranjan Prasad
(ranjeevphy@igcar.gov.in)

Course Details:

- Fracture Mechanism in Metals
- Linear Elastic Fracture Mechanics
- Elastic Plastic Fracture Mechanics
- Low Cycle Fatigue
- Assessment of Creep damage and creep-fatigue interaction
- Creep crack growth models
- Experimental determination of fatigue and creep curve CTOD, KIC, KIa, J-R curve and C*
- Basis of ASME Sec. XI Reference Curve and its use in Pressurised Thermal Shock
- CTOD design method
- J-Estimation Schemes and J-based failure assessment diagram
- Net Section Collapse Criteria and Reference Stress approach
- R-6 method and its application
- Thermal background of international assessment procedure
- RCCMR code/A-16 method and its application
- CEGB codes
- Application of R-5/R-6 for design of high temperature components
- Failure Assessment Diagram of PD-6493 and BS-7910
- J-Estimation Schemes and J-based failure assessment diagram
- Leak-Before-Break design method
- Analysis of numerical techniques/Computational fatigue, Fracture and creep
- Probabilistic Fatigue, Fracture and creep
- Bench Mark solutions
- Manufacturing and process-induced defects that influence structural integrity -
- Principles, capabilities and applications of surface examination NDE techniques
- Principles, capabilities and applications of volumetric examination NDE techniques
- Quality assurance of nuclear components with relevant codes and standards and quality concepts
- Structural integrity, in-service inspection and life assessment of nuclear components using NDE
- NDE Lab visit and Practicals

Course Outcomes:

This course develops expertise in fracture mechanics, fatigue, creep damage and creep–fatigue interaction for structural integrity assessment of nuclear components. Students gain proficiency in applying LEFM, EPFM, CTOD, J-integral, R-5/R-6 methods, Failure Assessment Diagrams, and ASME, RCC-MR and BS-7910 codes, integrated with NDE techniques for inspection and life assessment.

References:

1. Practical Non-destructive testing- Baldev Raj, Jayakumar.T. and Thavasimuthu. M., Narosa publishing house, New Delhi, 1997
2. Advances in NDE for structural integrity, - Nichols. R.W., Applied Science Publishers, London, 1982.

3. Non destructive Evaluation: A tool in Design, Manufacturing and Service and Francis – Don E.Bray and Roderick K. Stanley, Taylor, CRC Press, New york, 1996.
4. Non-destructive testing, R. Halmshaw, Edward Arnold, 1991.
5. Electrical and Magnetic Methods for Non-destructive testing, - J. Bllitz, Adam Hilger, Bristol, 1997.
6. Ultrasonic testing of materials, - Josef Krautkramer, Herbert Krautkramer, Springer-Verlag. January 1983.

ME5: Seismic Design of Nuclear Reactors and Facilities (20 Lecture Hrs)

Coordinator: Shri S. D. Sajish
(sajish@igcar.gov.in)

Course Details:

- **Introduction to Earthquakes:** Tectonic features, faults e.g., plate boundaries, intra faults, horizon of earthquakes, Definition of various terms e.g., focus, epicenter distances, energy release, relations of magnitude v/s energy, magnitude v/s peak ground accelerations, definition of various waves generated e.g., p-waves, recording of earthquake motions, strong motions, attenuation relations.
- **Design Basis Ground Motion and IS 1893 Spectra:** Selection of design magnitudes of earthquakes, Evaluation of peak ground accelerations, return/recurrence periods, spectral shapes, synthetic time histories, peak ground accelerations for various zones of India.
- **Introduction to Earthquake Engineering:** Equations of motion for simple systems, importance of inertia forces, elastic forces, energy dissipation and damping, natural frequencies, mode shapes, modal participation factors, evaluation of seismic forces for single and two degree freedom systems.
- **Analysis Procedures for multi degree freedom systems:** Formation of matrices for stiffness, mass and damping. Frequency evaluation methods-subspace iteration, lanczos. Response spectrum analysis-modal combinations. Time history analysis- Wilson-q, Newmark-b
- **Soil-Structure Iteration:** General requirements, types of foundations, evaluation of subsurface material properties such as shear modulus, material damping ration, Poisson's ration etc. Analyses-direct method, impedance method, foundation uplift analysis.
- **Analysis and design of Structures:** Modeling of structures considering soil-structure interaction, structure-equipment interaction, damping of the structures, analysis of structures, evaluation of seismic forces, design of structures for seismic loads.
- **Analysis and design of Equipment:** Modeling of equipment, structure-equipment interaction, equipment-piping interaction, damping of the structures, analysis of structures, evaluation of seismic forces, design of structures for seismic loads.
- **Analysis and design of Piping:** Modeling of piping, equipment-piping interaction, damping of the piping, analysis of piping, evaluation of seismic forces, and design of piping for seismic loads.
- **IS 1893, 2002, Indian Standard Criteria for earthquake resistant design:** Seismic Coefficient method, Importance factors for industrial systems, response reduction factors, ductility design provisions, seismic design of chimneys, towers as per IS 1893.
- **Testing:** Pseudo-dynamic testing, shake table testing, in situ testing, ambient testing, testing for functional requirements, determination of natural frequencies and damping.
- **Response Control and Retrofitting:** Merits of response control design, passive (EPD, LED, base isolation etc) and active control, various devices of active and passive control, various retrofitting techniques, FRP wrapping, steel plate wrapping.
- **Seismic Design of Nuclear Facilities:** Earthquake resistant design of nuclear facilities with limited radioactivity inventory such as Research Reactors, `Waste Management Plants suing IAEA-TECDOC-348, Design of nuclear fuel cycle facilities using IAEA-TECDOC-1250.
- **Seismic re-qualification of old plants:** Inelastic response spectra, push over analysis, retrofitting techniques.
- **Tutorials:** Simplified models for structures like towers, chimneys, simple frames, equipment like heat exchangers, pressure vessels and piping considering various support conditions like fixed-fixed, fixed-free, pin-pin, evaluation of seismic responses using first fundamental modes or peak values of design response spectrum.

Course Outcomes:

This course provides comprehensive knowledge of earthquake engineering principles, seismic analysis and design methodologies for nuclear structures, systems and components. Students develop capability to perform response spectrum and time history analysis, soil–structure interaction studies, and seismic qualification as per IS-1893, AERB guidelines, IAEA documents and USNRC practices.

References:

1. Chopra, A.K., "Dynamics of Structures, Theory and applications to Earthquake Engineering", Pearson Education Inc., 2003.
2. Ray W.Clough and Joseph Penzien, Dynamics of Structures", New York, McGraw-Hill Book Company.
3. Mariopaz, "Structural Dynamic (Theory and Computation)", CBS Publishers and Distributors, Delhi.
4. Bathe, K.J., and Wilson, E.L., "Numerical Methods in Finite Element Analysis", Englewood, N.J., Prentice-Hall.
5. ASCE 4-98, "Seismic Analysis of Safety Related Nuclear Structures and Commentary", ASCE, New York.
6. United States Nuclear Regulatory Commission (USNRC), 1990, Standard Review Plan
7. P.N. Agarwal, "Engineering Seismology", IBH Publishers, New Delhi.
8. Safety Guide, AERB/SG/D-23, "Seismic Qualification of structures, Systems and Components of PHWRS.
9. AERB/SG/S-11, 1990, "Seismic Studies and Design Basis Ground Motion for Nuclear Power Plant Sites". AERB, Mumbai, India.
10. IS: 1893 (Part 1,2 & 4) 2002, criteria for Earthquake Resistant Design", BIS, New Delhi.

ME15: Process Control & Instrumentation (20 Lecture Hrs)

Coordinator: Shri M. Saktivel
(saktivel@igcar.gov.in)

Course Details:

- Basic Concepts
- Units of measurements, Definitions (accuracy, precision, repeatability, span, range, hysterisis, drift, sensitivity, resolution, lag etc.) -- Sensors, transducers, Transmitters, PI diagrams, Symbols., Digital and analog devices.
- Sensing, Transmission, Receiving of the following Process Variables
- Temperature: classification, thermocouples, RTD, Thermistors, Pyrometers.
- Flow: Direct type, inferential type, constant area sensors, differential pressure meters, variable area meters, magnetic, ultrasonic, vortex type flow meters, and mass flow meters.
- Level: Direct type (Float, gauge glass, torque tube, piston tube, reflex etc) indirect type (Pressure gauge, purge, d/p with open/closed tanks, Ultrasonic, nucleonic, capacitance & conductivity).
- Pressure: Manometers, Bourdon, bellows, diaphragms, D/P Tx, (electronic & pneumatic), strain gauges, load cells.
- Analytical: pH, viscosity, conductivity, humidity, isotopic purity, and turbidity.
- Control System: Feedback Control theory, Modes of control, generation of control modes, Controllers, feedback & feed forward control, final control elements and valve positioners.
- Safety principles: Trip logic, annunciators, simple logic circuits, and smoke/fire detectors.
- Current Trends In Instrumentation: Smart transmitters, Instrumentation for a process loop, Paperless recorders, DAS, PLC, DRS, etc.

Course Outcomes:

This course imparts knowledge of process measurement, instrumentation and control systems used in industrial and nuclear applications. Students gain competence in sensors, transmitters, measurement of temperature, flow, level, pressure and analytical variables, and apply feedback and feed-forward control, safety logic, PLC, DCS and modern smart instrumentation.

References:

1. Instrument Technology Vol. I to V E.B. Jones.
2. Mechanical & Industrial Measurements, R.K. Jain
3. Automotive Process Control, Donald P. Eckman
4. Measurement Systems Application & Design, Ernest Doebelin.
5. Process Instrument & Control Handbook, Douglas Considine.
6. Instrument Engineers Handbook, Vol. I&II, Dela G. Liptak
7. Instrumentation for Process Measurement & Control, N.A. Anderson

DETAILED COURSE STRUCTURE

Foundation Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	MS1	Engineering Mathematics	35	2
2.	MS2	Computational Methods	30	2
3.	MS3	Materials and Metallurgy	25	1
4.	MS4	Reactor Physics and Fuel Design	30	2
5.	MS5	Health Physics	25	1
FOUNDATION TOTAL			**145**	**8**

Core Courses				
Sr. No	**Course Code**	**Subject Title**	**Hours (T)**	**Credits**
1.	MS6	Metallurgical Thermodynamics	30	2
2.	MS7	Experimental Methods for Materials Research	45	3
3.	MS8	Structural Materials for Nuclear Reactors	45	3
4.	MS9	NDE Science and Technology	30	2
5.	MS10	Physical Metallurgy	45	3
6.	MS11	Fuel Cycle Physics and Introduction to Fuel Cycle	30	2
7.	MS12	Introduction to Materials Science and Engineering	45	3
		CORE TOTAL	**270**	**18**

Electives (any four)					
Sr. No	**Course Code**	**Subject Title**	**Hours**		**Credits**
			(T)	**(L)**	
1.	MS13	Corrosion Science and Engineering	30	-	2
2.	MS14	Mechanical Behavior of Engineering Materials	30	-	2
3.	MS15	Manufacturing Technology	30	-	2
		ELECTIVES TOTAL	**90**	**-**	**6**

FOUNDATION COURSES COORDINATOR

Course	Coordinators	Contact
MS1: Engineering Mathematics	Dr. K. Natesan	22109/22856,natesan@igcar.gov.in
	Dr. V. Satish Kumar	26919/26977,vsatish@igcar.gov.in
MS2:Computational Methods	Dr. G. V. Prasad Reddy	21212/22216, prasadreddy@igcar.gov.in
MS3: Materials and Metallurgy	Dr. Vani Shankar	21147/22805,vani@igcar.gov.in
MS4:Reactor Physics and Fuel Design	Shri D. Nagasivayya	21232/22154,dnsiva@igcar.gov.in
MS5: Health Physics and Radiological Safety	Dr. S. Chandrasekaran	23556.schand@igcar.gov.in

CORE COURSES COORDINATOR

Course	Coordinators	Contact
MS6:Metallurgical Thermodynamics	Dr. C.Sudha	23634/22586,sudha@igcar.gov.in
MS7:Experimental Methods for Materials Research	Dr. S. Amrithapandian	22694/21905, pandian@igcar.gov.in
MS8:Structural Materials for Nuclear Reactors	Dr. S. Ningshen	22094/ 22116,ning@igcar.gov.in
MS9:NDE Science and Technology	Dr. Anish Kumar	23601/ 23602,anish@igcar.gov.in
MS10:Physical Metallurgy	Dr. Arup Dasgupta	22135/ 22586,arup@igcar.gov.in
MS11:Fuel Cycle Physics and Introduction to Fuel Cycle	Dr. Vidya Sundararajan	22474/22454,vidya@igcar.gov.in
MS12: Introduction to Materials Science and Engineering	Dr. R.Mythili	22207/21353,rm@igcar.gov.in

ELECTIVES COURSES COORDINATOR

Course	Coordinators	Contact
MS13: Corrosion Science and Engineering	Dr. S. Ningshen	22094/22116,ning@igcar.gov.in
	Shri M. V. Kuppusamy	22388/22395,masikuppu@igcar.gov.in
MS14:Mechanical Behavior of Engineering Materials	Dr. A. Nagesha	21080/ 22805,nagesh@igcar.gov.in
MS15: Manufacturing Technology	Dr. M. Vasudevan	21216,dev@igcar.gov.in

FOUNDATION COURSES

MS1: Engineering Mathematics (35 Lecture Hrs)

Coordinator: Dr. K. Natesan(natesan@igcar.gov.in),
Dr. V. Satish Kumar(vsatish@igcar.gov.in)

Course Details:

- Computer arithmetic and errors . Types of errors, error estimates and its propagation, Data analysis : Difference tables, Interpolation methods of Lagrange and Hermite, Chebyshev polynomials and Pade's approximation with rational functions. Numerical differentiation of interpolating polynomials. Numerical Integration : Trapezoidal, Monte-Carlo and Gaussian Quadrature methods Solution of algebric and transcendental equations, Newton-Raphson method, Graffe's root squaring method; Data approximation by method of least square, curve fitting.
- Linear vector space and subspaces, Basis, Gram-Schmidt orthogonalization, Linear system of equations: LU decomposition, Cholesky factorization and Gauss-Jordan technique. Iterative techniques using the methods of Jacobi, Gauss-Seidel and over relaxation. Convergence criteria and error estimation. Matrix inverse, Ill conditioned and sparse matrices. Bilinear forms, Principal axes transformation and eigen values, Determination of eigen values and eigen vectors. LU and QR algorithms, Singular matrices and singular value decomposition.
- Ordinary differential equations, Different types of differential equations, Lipschitz theorem and conditions for existence and uniqueness of solutions, Numerical methods for solving differential equations. Method of Euler, Adams and Runge Kutta, Predictor corrector method, Solving stiff equations.
- Probability and Statistics:Probability and Random variables, Binomial, Poisson and Normal distributions, Moments of a distribution, Counting experiments Estimation of model parameters, Confidence intervals, Testing of hypotheses, Goodness of fit, Chi-square test.
- Integral Transforms: Laplace transform, Linearity of LT, LT of derivatives and integrals, Solution of differential equations using LT, Response of electric circuits, Response of damped oscillator to a square wave, Differentiation and integration of LT.Periodic functions, Fourier series representation of functions, Even and odd functions, Determination of coefficients, Fourier integrals. Data compression, Hauffman coding and wavelet transforms.
- Partial Differential Equations, Finite difference method in one and two dimensions, Solution of steady and transient heat conduction and diffusion equations.
- Finite element method, Energy Theorem and integral equations, Weighted residual approximations, Point and subdomain collocation. Galerkin method, Variational principles and Lagrange multipliers. B-splines,Bezier curves, Response surface method, different levels of factorial design.

Course Outcomes:

On completion of this course, students will be able to apply numerical methods such as interpolation, numerical differentiation and integration, and solution of algebraic and transcendental equations with error estimation. They will develop proficiency in linear algebra, eigenvalue problems, differential equations, probability and statistics, and apply integral transforms, FEM, and PDE solutions to engineering and physical problems.

References:

1. Davis, H. T. and Thompson, K., Linear Algebra and Linear Operators in Engineering: with Applications in Mathematica, Academic Press, 2000.
2. Chapra, S.C. and Canale, R.P., Numerical Methods for Engineers, McGraw-Hill, 1985.
3. R. L. Burden and J. D. Faires, Numerical Analysis, 6th ed., PWS-Kent Publishing, 1997.
4. Krishnamurthy, E. V., Computer based numerical algorithms, East West Press, 1976.
5. Gupta, S.K., Numerical methods for Engineers, Wiley (1995).
6. Press, W.H.; Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P., Numerical Recipes in Fortran (or C), Cambridge University Press (1992).
7. Scarborough, J. B. Numerical Mathematical Analysis, Oxford and IBH Publishers, 1968.

MS2: Computational Methods (30 Lecture Hrs)

Coordinators: Dr. G. V. Prasad Reddy
(prasadreddy@igcar.gov.in)

Course Details:

- Programming: Introduction to programming with C# as the reference language (C# software will be provided for practice), Getting familiarized with Matlab
- Numerical Techniques: Overview of standard numerical techniques with wpecial emphasis on statistics and solving ordinary and partial differential equations
- Optimization: Overview of techniques with special emphasis on non-linear optimi9zation using gradient descent, conjugate gradient and genetic algorithm
- Neural network for predictive applications: Overview of various neural network architectures, Multilayer perceptron model for prediction, need for neuro-fuzzy models
- Atomistic modeling: Introduction to Monte-Carlo Simulation, Basics of molecular dynamics, prediction of thermo-physical properties by molecular dynamics, computational Challenges
- Introduction to application of FEM: Introduction to FEM and its application, demonstration of few simple application using Abaqus (FEM software)
- Current status in modeling and simulation: With respect to mechanical metallurgy

Course Outcomes:

Students will acquire working knowledge of programming using C# and MATLAB for scientific and engineering computations. They will be able to apply numerical techniques, optimization methods, neural networks, atomistic modeling, and FEM tools for modeling, simulation, and prediction in mechanical metallurgy and related domains.

References:

1. Sams Teach Yourself C# in 21 Days, B.L. Jones, SAMS publications
2. Numarical Recipes in C++: The art of scientific computing, *W.H. Press et al*, Cambridge University Press
3. Numerical Mathematical Analysis *J.B. Scarborough, MacMillan Publishers*
4 Genetic algorithms in search, optimization and machine learning, *D.E. Goldberg, Addison Wesley*
5. Guide to neural computing applications, *L. Tarassenko, Arnold publishers*
6. Monte Carlo Basics, *K.P.N. Murthy, ISRP publishers*
7. Molecular Dynamics Simulation by *J.M. Haile, John Wiley and sons*

MS3: Materials and Metallurgy (25 Lecture Hrs)

Coordinator: Dr. Vani Shankar
(vani@igcar.gov.in)

Course Details:

- Classification of Materials: Structure, Ferrous and non-Ferrous metals, Polymers, Ceramics, Composites, Electronic materials, Nano-structured materials.
- Selection of Materials: Classification of carbon steel, low alloy, carbon molybdenum, ferritic, austenitic and martenistic stainless steel. Selection and application of advanced alloys, stainless steels, Cr-Mo steels, Ti-alloys
- Heat Treatment and Mechanical Testing of materials including standards and specifications: Mechanical properties of materials & their evaluations as per ASTM or equivalent standards, tension, hardness, creep, fatigue (low & high cycle) & impact toughness tests.
- Metal Forming, Welding Science & Technology: Metal fabrication technologies, rolling, forging, extrusion, deep drawing and introduction to material modelling. Welding metallurgy for stainless steels, ferritic steels, dissimilar metal welds and Ti-alloys, hard-facing and repair welding.
- Metallographic Examination: Experimental techniques for characterization of microstructure (Optical, TEM/SEM and microscopic techniques) specimen preparation and evaluation of microstructure of different materials.
- Corrosion: Galvanic, Uniform, Crevice, Stress corrosion cracking, Corrosion fatigue, Corrosion fast reactors and re-processing plants, Corrosion test methods and standards.
- Non-destructive evaluation techniques for materials and components: Visual, LPT, MPT, UT, Eddy current, X-ray Radiography, Neutron, Gamma ray etc. for quality assurance and in-service inspection.
- Nuclear Fuels: Production, fabrication, properties and application of nuclear fuels (metallic fuels, ceramic fuels (oxide, mixed oxide, mixed carbide)) and heavy water. Radiation damage and post irradiation examination of core materials.

Course Outcomes:

Students will be able to classify and select engineering and nuclear materials based on structure–property relationships, processing routes, and service requirements. They will gain competence in heat treatment, mechanical testing, welding metallurgy, corrosion mechanisms, metallographic characterization, NDE techniques, and nuclear fuels and radiation damage.

References:

1. Introduction to Materials Science for Engineers - James Shackelford
2. Physical Metallurgy Principles & Practice - V.Raghavan
3. Introduction to Solids - L.V.Azaroff
4. Structure and Properties of Materials - Wulff Series, Wiley Eastern, New Delhi
5. Materials in Nuclear Application - C.K.Gupta
6. Nuclear Chemical Engineering - Benedict and Pigford
7. Physical Metallurgy, Reed – Hill
8. Heat treatment of steel – Avener
9. Introduction to Solid State Physics - Charles Kittel (Wiley Eastern)
10. Physical Metallurgy: Principles and Practice - V. Raghavan (Prentice Hall)
11. The Physics and Chemistry of Materials - Joel Gersten and Fiedenick Smith (Wiley, Canada)
12. Fundamentals of Materials Science and Engineering - D. Callister (Wiley, Europe)

MS4: Fast Reactor Physics and Fuel Design (30 Lecture Hrs)

Coordinators: Shri D. Nagasivayya
(dnsiva@igcar.gov.in)

Course Details:

- Basic Nuclear Physics Concepts: Properties of nuclei. Nuclear forces, Nuclear models. Nuclear decay, Liquid drop model and nuclear stability, Nuclear reactions including fission, Compound nucleus formation, Microscopic cross-section, Partial and total cross- sections.

- Basics Neutron Physics Concepts: Introduction to physics of fission process. Definition of flux current and sources, Neutron-nuclear interaction cross sections, Reaction rate density, macroscopic cross section and mean free path. Cross-sections of elements, compounds and mixtures.

- Chain Reaction: four factor formula; definitions of k-infinity, k-effective w.r.t. neutron balance equation (with diffusion approximation); boundary conditions; definition of reactivity; criticality.

- Homogeneous Reactor: Space dependence of neutron flux. Flux shape in different geometries, Slab/cylinder/spherical reactor, Geometric and material, buckling. Diffusion length, reflected slab, reflector saving. Heterogeneous reactors; typical examples.

- Reactor Kinetics: Time dependent diffusion equation, Point kinetics, Prompt neutrons, Delayed neutron precursors, Reactor period, period versus reactivity, Inhour formula, one group delayed neutrons, one dollar of reactivity, Prompt and delayed criticality. Feedback coefficients.

Course Outcomes:

On successful completion, students will understand nuclear structure, fission physics, neutron interactions, and chain reactions relevant to fast reactors. They will be able to analyze neutron diffusion, reactor criticality, kinetics, feedback effects, and apply these principles to fast reactor fuel and core design.

References:

1. The Elements of Nuclear Reactor Theory, Samuel Glasstone and M.C. Edlund. Van Nostrand, 1952.
2. Introducation to Nuclear Reactor Theory, Lamarsh J.R., ANS, 2002
3. Physics of Nuclear Reactors, Jakeman D., English Universities Press, 1966.
4. A.E. Walter and A.B. Reynolds, “Fast Breeder Reactors”, Pergamon Press, 1981.

MS5: Health Physics & Radiological Safety (25 Lecture Hrs)

Coordinator: Dr. S. Chandrasekaran

(schand@igcar.gov.in)

Course Details:

- Introduction: Radiation sources: Natural and Induced radioactive sources, units of radioactivity, half-life and decay constant, specific activity. Basic interaction mechanism of a) alpha b) Beta c) Gamma/X-rays d) Neutrons with matter. Definition of various dosimetric terms (exposure, absorbed/equivalent/effective dose, concept of radiation/tissue weighting factors and their importance (SI units & new units). Concepts of Exposure measurement: Free air and Air wall chambers, Exposure-dose relationship, Bragg-Gray principle.
- Biological effects of Radiation: Human body: Cells, tissues and organs, structure of cell, cellular effects. Factors, which influence the damage of cell. Interaction of radiation with biological matter. Radiation effects: stochastic and deterministic. Acute and delayed effects. Types of exposure (natural, occupational, medical and public).
- Radiation Protection and Regulations:
  - Importance of radiation protection program in DAE, Atomic Energy act, National and International regulatory bodies, their role and responsibilities., Radiation Protection Rules, Dose limits stipulated by these bodies. Dose limits observed in India.
  - Radiation protection philosophy, Principles of radiation protection, concept of ALI & DAC (with suitable problems). Fundamentals of ICRP respiratory model, entry through ingestion, GI track model.
  - Principles of radiation detection and monitoring: Basic operating principles of a) Gas b) Scintillation (including thermo luminescence detectors) and c) Semiconductors detectors.
  - Type of Radiation monitors/Radioactivity measurement methods adopted for radiation protection.
- Radiation protection and measurement (External and Internal):
  - Control of external exposures (with problems in each case).
  - Buildup concept, shielding from alpha, beta, gamma and neutron sources. Shielding from mixed sources.
  - Routes of intake of radioactive material,
  - Radiotoxicity and classification of laboratories, design of laboratory for radioactive work, Radioactive waste classification and management. Personal monitoring, area-monitoring, air monitoring. Bioassay, whole body counting techniques. Use of personal dosimeters (TLDs, pocket dosimeters)
- Radiation Protection procedures: Procedures followed in radiation work places, work permits, zoning concept, contamination control methods, and rubber areas, spill pack (gloves + absorbing paper), Decontamination techniques. Precautions during radioactive source storage and handling, safety during transportation. Nature of duties and responsibilities of Radiation Safety Officer/Health Physicist.
- Nuclear Accidents, Emergency Preparedness and Management: Reasons for accidents, classifications of accidents, International Nuclear Events Scale. Types of emergency, emergency preparedness.
- Radiological aspects and Environmental Impact of FBRs: Radiological aspects of Fuel Cycle Facilities
- Industrial Safety Aspects: Introduction to Industrial Safety (accident prevention technique, Job safety analysis, control measures), Factories Act, 1948 & Atomic Energy Factories Rules, 1996,ndustrial safety aspects (Physical and Chemical Hazards),Industrial safety aspects (safety in Machineries, hand tools & Material handling equipments, personal protective equipments, etc)Construction safety (includes Electrical Safety & Work Permit System)

Course Outcomes:

Students will gain the ability to evaluate radiation sources, interaction mechanisms, dosimetric quantities, and biological effects of radiation. They will apply radiation protection principles, shielding calculations, monitoring techniques, regulatory frameworks, and emergency preparedness concepts for safe operation of nuclear and radiological facilities.

References:

1. Introduction to Health Physics – Herman Cember
2. Introduction to Radiation Protection – Alan Martin
3. IAEA Regional Basic Professional Training Course on Radiation Protection (Course jointly organized by BARC and IAEA), October 26-Dember 18, 1998
4. Nuclear Radiation Detection - W.J. Price
5. Radiation Detection and Measurement - G.F. Knoll
6. Biological Effects of Radiation – J.E. Coggle
7. Nuclear Radiation Detectors by S.S. Kapoor and V.S. Ramamurthy (Publication: New Delhi, Wiley Eastern Ltd, 1986)
8. Atoms, Radiation and Radiation Protection by James E. Turner 1986
9. Problems and solutions in Radiation Protection by James E. Turner, 1988
10. Guide Lines for Hazard Evaluation Procedures – American Institute of Chemical Engineers
11. Risk Analysis in the Process Industries: The Institute of Chemical Engineers, England.
12. Loss Prevention in The Process Industries: Hazard Identification, Assessment and Control; Vol-1, 1996 2 Edition, Frank P Lees.

CORE COURSES

MS6: Metallurgical Thermodynamics (30 Lecture Hrs)

Coordinators: Dr. C. Sudha
(sudha@igcar.gov.in)

Course Details:

- **Classical T hermodynamics -** the scope of classical thermodynamics, basic concepts and definitions. First and second laws of thermodynamics and its applications.
- Thermodynamic Properties of pure substances and mixtures.
  The chemical potential, fugacity, activities, and activity coefficients, Phase rule
- Solubilities of gases in liquids, and solids
- **Solution Thermodynamics**: Integral and Partial Molar Thermodynamic Properties, Solution Models, Ideal Solution, Regular Solution, Real Solutions
- **Phase Equilibrium and Stability**: Phase equilibria in multicomponent systems, phase diagrams, the differential approach for phase equilibrium relationships, pressure-temperature relations,
- **Chemical Reaction Equilibria**: Equilibrium constants for Homogeneous and heterogeneous reactions.
- Graphical Representation of Thermodynamic Information, Ellingham Diagrams, Predominance Area Diagrams, Pourbaix Ellingham Diagrams, Phase Diagrams,
- **Experimental Methods**: Methods for Determining Thermodynamic Properties, Presentation of Thermodynamic Data, Examples of Calculations.

Course Outcomes:

Students will develop the ability to apply classical thermodynamics, including the first and second laws, to materials systems involving pure substances and multicomponent solutions. They will analyze chemical potential, activity, fugacity, phase equilibria and reaction equilibria, and interpret Ellingham, predominance area and phase diagrams for materials processing and stability assessment.

References:

1.D. Gaskell, Materials Thermodynamics, Talyor and Reid, 1981.
2. O. Kubaschewski, C.B. Alcock and P.J. Spencer, Materials Thermochemistry, Pergamon, 1985

MS7: Experimental Methods for Materials Research (45 Lecture Hrs)

Coordinators: Dr. S. Amirthapandian
(pandian@igcar.gov.in)

Course Details:

- Vacuum Techniques (3): Fundamentals, Creation & Pressure Measurements, units, Pumps fore Vacuum, high Vacuum and UHV
- Thin Film synthesis methods- Physical, Chemical and MBE

- **3 X-RAY TECHNIQUES**
  - techniques based on measuring the energy or angular distribution of scattered x-rays,
  - Wide angle elastic scattering (XRD): Atomistic – form factors; unit cell structure factors, Bragg equation, reciprocal lattice, Laue equations; Expwrimental methods- transmission, reflection, thin film, in-situ; Otjer information-particle size distributions
  - Inelastic scattering- x-ray absorption spectroscopy: Basics- edges and extended fine structure; XANES and EXAFS quantitation; Surface sensitivity; Experimental method
  - Small angle scattering-SAXS: Basics- what SAXS sees; Mathematical modeling
  - X-ray fluorescence spectroscopy: Basics- core hole formation, fluorescence yield, transport ("ZAF"); Experimental realization – Bulk analysis; lab and synchrotron x-ray sources; Surface analysis – TXRF; Microscopy – x-ray beam manipulation

- **ELECTRON MICROSCOPIES**
  - **Transmission electron microscopy (TEM/STEM):** Electron interactions in solids-elastic and inelastic scatterin, phase change; Contrast generation- bright field, dark field, "high-resolution"; Images-information and resolution; Diffraction; Beam damage; Experimental methods hardware, specimen preparation; Inelastic scattering- electron energy loss; Emitted x-rays – elemental analysis, sensitivity, spatial resolution; STEM
  - **Scanning electron microscopy:** Beam transport in bulk solids; Signals and images- backscattered and secondary electrons; Diffraction- channeling patterns – EBSD; X-ray generation and transport, detection and analysis; Other useful signals; Experimental methods;
  - EPMA Electron probe micro-analyzer

- **LEELSION BEAM TECHNIQUES**
  - Techniques using ions or neutrals made from them as the bombarding species
  - Ion beams – production-ion guns; manipulation- ion, filters
  - Rutherford (Nuclear) Backscattering Spectroscopy- (RBS): High energy ions in solids- electronic and nuclear (Rutherford) stopping; Quantitative description; Experimental methods – energy spectroscopy Nuclear reaction analysis – elemental specificity – depth profiling
  - PIXE (Proton Induced X-ray Emission) Signal to noise ratio – trace element analysis
  - Surface Mass Spectroscopy-SIMS:
  - Ejection of matter by bombardment: sputterin; Fate of ejected materials subsequent reaction, charge state; Mass detection – quad, magnetic sector, ToF; experimental issues

- **ELECTRON SPECTROSCOPIES**
  - Techniques based on measuring the energy distribution of emitted electrons

- Photoelectron spectroscopy: Basics- energy balance, element identification; Not-so Basics- relaxation, chemical states, satellites; Surface sensitivity; Quantitation; UPS- the unfamiliar cousin
- Auger Electron Spectroscopy: Electron excitation- why bother ? The Auger spectrum- energy balance; Chemical effects; Quantitation; Imaging- meaning of maps.
- Experimental methods; Surface of real-world things; Below the surface- profiling, variable energy; Hardware and software; samples and handling

- **PROXIMAL PROBE MICROSCOPIES**
  Scanning Tunneling Microscopy (STM) and Atomic Force Microscopy (AFM): Basics; Experimental methods; Spectroscopy in Scanning Probe Microscopy

- **NUCLEAR SPECTROSCOPY**
  Positron annihilation, Mossbauer – Application to defects, radiation damage defects in metals and alloys

- **VIBRATIONAL SPECTROSCOPIES**
  - Vibrations in molecules and solids – normal coordinates, group frequencies
  - Infrared spectroscopy;
  - IR absorption – dipole scattering, selection rules; Optical arrangements-transmission, specular reflectance, diffuse reflectance, attenuated total reflectance, microscopy, in-situ; Signal collection and Fourier transform processing, data analysis
  - Raman: Energy transfer, selection rules; Normal, resonance, surface-enhances, Fourier Transforms, UV

- **RESONANCE ABSORPTION SPECTROSCOPIES**
  - Nuclear Magnetic Resonance (NMR): Fundamentals; Experimental Techniques; Magnetic Resonance Imaging
  - Electron Paramagnetic Resonance (EPR): Fundamentals; Experimental Techniques

Course Outcomes:

This course enables students to select and apply advanced materials characterization techniques based on X-ray, electron, ion, nuclear and vibrational spectroscopies. Students will gain competence in XRD, TEM, SEM, RBS, SIMS, XPS, STM/AFM, IR, Raman, NMR and EPR, and interpret experimental data for structural, chemical and defect analysis of materials.

References:

1. Cullity Addision, B.D., “Elements of X-ray Diffraction”, Wesley Publishing Co., 1967.
2. Williams (D B), Carter (C B), Transmission Electron Microscopy: A Textbook For Materials Science, New York, Plenum, 1996
3. J.R. Tesmer et al ‘Handbook of modern ion beam materials analysis’ (MRS, Pittsburgh,1995)
4. L.C. Feldman, J.W. Mayer ‘Fundamentals of surface and thin film analysis’ (North- Holland, N.Y, 1986)
5. Prutton, M., “Surface Science and Technology, Volume27, “Analytical techniques for thin films”, Academic Press, Inc.Newyork, 1991.
6. Bacon, G.E., “X-ray and Neutron Diffraction”, Pergamon Press, 1966.
7. Concise Encyclopedia Of Materials Characterization Ed. Cahn (R W) and lifshin (E) Ed Oxfod, Pergamon, 1993
8. Advances in Materials Characterization Ed. G. Amarendra, Baldev Raj, M.H. Manghnani, University Press (India), 2007

MS8: Structural Materials for Nuclear Reactors (45 Lecture Hrs)

Coordinators: Dr. S. Ningshen (ning@igcar.gov.in)

Course Details:

- Three stage Nuclear Power Program (Importance of Material Selection)
- **Thermal Reactors:** Concept**,** Selection of Materials – Core and out of core**,** Processing of Materials**,** Properties/Performance of Materials
- **Fast Breeder Reactors:** Concept**,** Selection of Materials for different systems, Brief description of different systems**,** Core materials**,** Design criteria for clad and wrapper**,** Radiation damage**,** Evolution of materials for clad and wrapper**,** Material performance**,** Material processing and fabrication**,** Structural materials**,** Design criteria**,** Materials processing and fabrication**,** Steam generator materials**,** Design criteria**,** Selection of materials**,** Materials processing and fabrication**,** Properties of materials and performance
- **Materials in Reprocessing Applications,** Closing of nuclear fuel cycle**,** Design concept of reprocessing plant component**,** Selection of materials**,** Processing and fabrication**,** Evaluation of properties and performance
- **Materials in Waste Storage Applications**

Course Outcomes:

Students will gain comprehensive understanding of materials selection, processing and performance for thermal and fast breeder reactor systems under irradiation and high-temperature environments. They will analyze radiation damage, design criteria for clad, wrapper, steam generator and reprocessing plant materials, and evaluate materials for fuel cycle closure and waste storage applications.

References:

1. Materials research: Current scenario and future projections, Chidambaram R, Banerjee S Ed, Allied Publishers, New Delhi, 2003
2. High temperature reactor materials (workshop La Jolla,CA March18-21,2002), Allen T, Oak Ridge, U.S.Department of Energy, 2002.
3. Nuclear materials: Issues and concerns Vol 2., Bhaskara Rao D Discovery Publishing House, New Delhi, 2001.
4. Materials R & D for PFBR: Compilation of articles: (Eds) S.L. Mannan and M.D. Mathew, IGCAR, Kalpakkam, 2003.
5. An overview of R&D on fast reactor fuel cycle, Baldev Raj, Int. J. Nuclear Energy Science and Technology, Col.1, Nos.2/3, 2005, pp.164-177.
6. Selection of materials for PFBR, S.L. Mannan, S.C. Chetal, Baldev Raj, S.B. Bhoje, Trans IIM, Vol..56, No.2, April 2003, pp.155-178.
7. Development of fuels and structural materials for fast breeder reactors, Baldev Raj, S.L. Mannan, P.R. Vasudeva Rao and M.D. Mathew, Sadhana, Vol.27, Part 5, October 2002, pp. 527-558
8. Input of the atomic energy programme on special materials development in India, C. V. Sundaram, Trans IIM, vol. 41, No.5, Oct 1988, p.407.
9. Recent trends in fast breeder reactor materials, C.V. Sundaram, P. Rodriguez and S. L. Mannan, IE (I) Journal –MM, Vol.67, Sept. 1986, pp.1-11.
10. Radiation effects in nuclear reactor materials – correlation with structure, P. Rodriguez, R. Krishnan and C.V. Sundaram Bull. Mater. Sci. Vol. 6, No.5, May 1984, PP.339-367.

Nuclear Reactor Materials, C.O.Smith, Addison Wesley, 1967

MS9: NDE Science and Technology (30 Lecture Hrs)

Coordinators: Dr. Anish Kumar
(anish@igcar.gov.in)

Course Details:

- Introduction to NDE: Importance and need for NDE, classification of techniques,
- origin of defects; material processing related-casting, forging, rolling, welding etc., and service related-fatigue, creep, corrosion, irradiation etc. Detection, characterization, sensitivity, reliability, accuracy
- Surface NDE: Principle, instruments & sensors, capabilities, applications and limitations of visual, liquid penetrant, magnetic particle, eddy current and flux leakage techniques
- Volumetric NDE: Principle, instruments & sensors, capabilities, applications and limitations of radiography and ultrasonic techniques. Gamma, Micro-focal, LINAC and real-time radiography and tomography. IRIS, TOFD, SAFT, MEMS, Non-linear ultrasonics related to ultrasonics.
- Dynamic NDE: Acoustic emission, infrared radiography, intelligent processing of materials and continuous monitoring.
- Digital NDE: Forward and inverse problems, signal processing, numerical modeling, imaging, automation, probability of detection (POD), multiple NDE, data fusion and robotics.
- Industrial NDE: NDE for quality assurance, structural integrity, material characterization, condition monitoring and in-service inspection, reference standards for calibration, codes & standards, selection of NDE techniques
- Practicals:
  - Ultrasonic testing – detection of defects in weld/HAZ and measurement of thickness
  - X-radiography of welds and interpretation of radiographs
  - Eddy current testing of plates and heat exchanger tubes for defects
  - Seminar: Preparation and submission of report on a topic in advanced NDE. Presentation and viva-voce

Course Outcomes:

This course develops expertise in non-destructive evaluation principles for detection and characterization of manufacturing- and service-induced defects. Students will apply surface, volumetric, dynamic and digital NDE techniques, including ultrasonics, radiography, eddy current, acoustic emission and data fusion, in accordance with codes, standards and structural integrity requirements.

References:

1. A practical NDT – Baldev Raj, T. Jayakumar and M. Thavasimuthu, Narosa, New Delhi, 1996.
2. ASNT Volumes on Visual, penetrant, magnetic particle, eddy current, ultrasonic, radiography, acoustic emission, thermography and other techniques, ANST, Ohio, Coloumbus.
3. Grandt, A. F. Jr., Fundamentals of Structural Integrity: Damage Tolerant Design and Non-destructive Evaluation, John Wiley & Sons, Inc. Hoboken, NJ, 2004.
4. Bray, D.E. and R.K. Stanley, 1997, Nondestructive Evaluation: A Tool for Design, Manufacturing and Service; CRC Press, 1996.
5. Peter J. Shull, Nondestructive Evaluation: Theory, Techniques, and Applications, Marcel Dekker Inc., 2002.

MS10. Physical Metallurgy (45 Lecture Hrs)

Coordinators: Dr. Arup Dasgupta
(arup@igcar.gov.in)

Course Details:

- Structure and Properties of Materials
- Crystalline solids: Introduction: Engineering materials, materials cycle, application and selection criteria of materials. Significance of microstructure; crystalline defects:- dimensions, origin and their effect on properties; amorphous structure
- Phase diagrams: Origin, construction, interpretation and application of binary phase diagrams with reference to a few important metallic and ceramic systems. introduction and classification of phase transformations, calculation of phase equilibria based on thermodynamic principles
- Correlation between Free energy, selection of a Phase and order parameter, different thermodynamic classification of phase transformations, order of a transformation
- Diffusional transformations: Diffusion in solids: phenomenological approach and atomistic approach. Nucleation and growth theories of vapour to liquid, liquid to solid, and solid to solid transformations; homogeneous and heterogeneous strain energy effect during nucleation; interface-controlled growth and diffusion controlled growth; overall transformation kinetics. Principles of solidification, evolution of microstructures in pure metals and alloys. Precipitation from solid solution: types of precipitation reactions, crystallographic description of precipitates, precipitation sequence and age hardening, spinoidal decomposition.
- Iron-carbon alloy system: Iron-carbon diagram, nucleation and growth of pearlite, cooling of hypo-eutectoid, eutectoid, and hyper-eutectoid steels, development of microstructures in cast irons. Heat treatment of steels: TTT and CCT diagrams
- Diffusionless transformations: martensitic transformation, hardenability, role of alloying elements in steels. Bainitic transformation, Widmanstatten transformation, Massive transformation. Order-disorder transformation.
- Diffusion, rate theory, mechanisms of, measurement techniques
- Phase transformations in some nuclear non-ferrous metals and alloys
- Characterization of microstructure – microscopy techniques, X-ray spectroscopy and diffraction.
- Metallographic techniques: Optical metallography, image analysis, quantitative phase estimation.
- Properties of X-rays: continuous and characteristics x-rays, absorption, filter, production and detection of X-ray Diffraction methods: X-ray diffraction, X-ray topography, residual stress measurement techniques, small angle X-ray and neutron scattering.
- Electron optical methods: (a) Scanning electron microscopy and X-ray microanalysis including electron probe microanalysis, electron optics, electron beam specimen interaction, image formation in the SEM; (b) Transmission electron microscopy and analytical transmission electron microscopy: Electron diffraction, reciprocal lattice, analysis of SAD patterns; different electron diffraction techniques, atomic resolution microscopy, analytical devices with TEM, field ion microscopy, scanning tunneling microscopy, advanced techniques.
- Introduction to novel materials and processes: Composites, intermetallics, cermets, metallic foams, intelligent materials, Dependence of their properties on structure, Nanocrystalline Materials: Synthesis, Structure and Properties.: Amorphous Materials; Metallic glasses, Glass forming ability, Bulk Metallic Glasses, Properties; Quasi crystalline Materials; Structure, Synthesis, Properties;
- Advanced Processes: Rapid solidification processing, Laser surface Modification, Mechanical Alloying, Rapid prototyping, Self propagating High temperature synthesis, inert gas condensation etc.
- LABORATORY Microstructures of alloys of Fe, Al, Cu and Ti for each type of transformation at different levels of resolution; Crystal structure by diffraction techniques; Defects of different

dimensions; Advanced processes – Laser Ablation, Magnetron Sputtering and Plasma and Chemical deposition methods.

Course Outcomes:

Students will develop deep understanding of structure–property–processing relationships through crystal structures, phase diagrams, diffusion and phase transformations. They will analyze solidification, precipitation, martensitic and diffusional transformations, and apply microscopy and diffraction techniques to characterize microstructure and mechanical behavior of engineering and nuclear materials.

MS11: Fuel Cycle Physics& Introduction to Fuel Cycle (30 Lecture Hrs)

Coordinators: Dr. Vidya Sundararajan
(vidya@igcar.gov.in)

Course Details:

- Basic fuel cycles – once through and multiple recycle strategies, neutron economy, fissile material conservation and three stage program of India.
- Physics of U exploration methods. Recovery of the starting compounds bearing U,Pu,Th from their primary and secondary sources. Mining and milling. Beneficiation, preconcentration, purification and recovery. Radio-activity of mill tailings.
- Methods of U enrichment
- Oxide fuels: Preparation of UO2, PuO2, MOX and ThO2. Physical and chemical properties. Phase diagrams of relevance.
- Advanced ceramic fuels : carbides and nitrides
- Metal and Alloy fuels: Preparation of U, Pu, Th. Historical over view of the alloy fuel development, alloys (U-Zr, U-Pu-Zr, U-Pu-Minor Actinide). Dispersions and composites. Salient physical and chemical properties. Relevant phase diagrams. Fabrication and quality control.
- Inert matrix fuels for partitioning and transmutation – A brief account of the current developments.
- Fuel fabrication and criticality safety. Fresh and spent fuel transport and storage in SFSP and burnup credit. Transport of fresh and irradiated fuel.
- U-Pu cycle: U, U-Pu (MOX), Th-U cycle. Examples in thermal and frast reactor systems.
- Enrichment versus discharge burn up; enrichment versus reactivity coefficients; fertile host versus inert matrix.
- Fuel cycle indices - Conversion and breeding ratios; reactor doubling time. Fuel and system doubling times.
- Fissile and fertile actinides and MA (inventory and isotopic vector) in discharged fuel in different fuel cycles; Long lived fission products (LLFP).
- Issues related recycling – Effective fissile content of discharged fuel for next cycle; refabrication of fuel for the next cycle. Results of Pu composition change with once through, one recycle and multiple recycle in thermal and fast systems.
- Activity and toxicity of discharged fuel – FPs and actinides; activation of structural materials. Fuel reprocessing – thermal and fast reactor fuel - U-Pu, U-Th and U-Pu-Th fuels.
- Isotopic separation operation of bred uranium in thorium cycles to remove U-232.
- MA and LLFP incineration. Waste management strategies; different levels of waste, LLW and HLW. Methods of dilution, discharge and fixation; long term storage in geological structures.

Course Outcomes:

This course enables students to understand the physics and technology of nuclear fuel cycles, including once-through and multiple recycle strategies. Students will analyze fuel fabrication, enrichment, burnup, breeding ratios, actinide inventories, reprocessing, waste management and partitioning–transmutation, with application to thermal and fast reactor systems.

References:

1. F.J.Rahn et al., A Guide to Nuclear Power Technology, John Wiley and Sons (1984).
2. R.G.Cochran and N.Tsoulfanidis, Nuclear Fuel Cycle Analysis and Management, ANS (1990).

MS12: Introduction to Materials Science & Engineering (45 Lecture Hrs)

Coordinators: Dr.R.Mythili
(rm@igcar.gov.in)

Course Details:

- **Structure, Bonding & Defects in Solids:** Single crystal & polycrystalline materials, Unit cell, Crystal symmetry, Bravais lattices, point groups & space groups, Miller indices, Cohesive forces in crystals, Madelung energy and its calculation for NaCl and CsCl, Crystal structures, Close packing, Ionic Radii and Radius ratios, Common crystal structures of elements & compounds, Factors influencing crystal structures, Structure-property relations, Defects in solids, Thermodynamics of defect formation, Non-stoichiometry, Ionic conduction, Solid electrolytes.

- **Diffraction Techniques:** Diffraction phenomenon, X-ray, neutron and electron diffraction, Bragg's Law, Size and shape of unit cell, Basics of crystal structure determination, Powder diffraction and single crystal methods, Phase identification by XRD, Powder diffraction data base, Indexing of diffraction patterns and lattice parameter calculation, Rietveld refinement, Particle size & residual stress determination by XRD.

- **Microstructure & Microscopy:** Microstructure - origin and significance, Optical & electron microscopy

- **Physical Properties:** Mechanical properties, Fracture, Strengthening mechanisms, Thermal expansion, Thermal conduction, Thermoelectric effects, Electrical and magnetic properties - metals, semiconductors and insulators, Band picture of solids, Ferroelectric materials, Superconductors, Magnetic properties, Magnetic domains, Optical properties, Non-linear optical properties, Lasers, Fiber optics & applications.

- **Chemical Reactivity of Solids:** Factors affecting chemical reactivity, Diffusion, Surfaces of solids, Surface analysis techniques – ESCA, Materials at very low and high temperatures, Materials under pressure, Radiation damage in solids, Corrosion.

- **Synthesis of Materials:** Solid state reactions, Wet chemical reactions and precursor techniques, Combustion synthesis, Sol-gel process, Soft chemical reactions, Crystal growth techniques with examples, Thin films, Nanocrystalline materials, Sintering.

- **Phase Diagrams &Phase Transformations:** Phase diagrams – significance, experimental & computational methods of phase diagram determination, Classification of phase transformations, Order-disorder transitions, Nucleation and growth theory, diffusion-controlled and diffusion less transformations, Thermal analysis techniques.

Course Outcomes:

Students will gain foundational knowledge of structure, bonding, defects, diffusion and phase transformations in solids. They will apply diffraction, microscopy and spectroscopy techniques to relate mechanical, electrical, magnetic, optical and chemical properties with structure, and understand materials synthesis, corrosion and radiation damage.

References:

1. Materials science and technology: a comprehensive treatment, (18 Vols.) Ed. R.W. Cahn, P. Haasen and E.J. Kramer, VCH, Weinheim, 1991.
2. Encyclopedia of materials: science and technology, (11 Vols.) K.H.J. Buschow et al., Elsevier, Amsterdam, 2001.
3. Introduction to solid state physics, C. Kittel, VII Ed, John Wiley & Sons, 1996.
4. Solid state chemistry and its applications, A.R. West, John Wiley & Sons, 1984.
5. The structure and properties of materials, (4 Vols.) Ed. J. Wulff, Wiley Eastern, 1974.
6. Materials science and engineering: an introduction, V Ed, W.D. Callister, John Wiley&Sons, N.Y., 2003.
7. Introduction to materials science and engineering, K.M. Ralls, T.H. Courtney and J. Wulff, Wiley Eastern, 1978.
8. Elements of x-ray diffraction, B.D. Cullity, Addison – Wesley, 1978.
9. Analytical chemistry by open learning: X-ray methods, C. Whiston, John Wiley & Sons, 1987.
10. X-ray diffraction: a practical approach, C. Suryanarayana and M. Grant Norton, Plenum, 1998.
11. The science and engineering of materials, IV Ed D.R. Askeland and P.P. Phule, Brooks/Cole, 2003.
12. The physics and chemistry of materials, J.I. Gersten and F.W. Smith, John Wiley & Sons, 2001.
13. Metallic materials: physical, mechanical and corrosion properties, P.A. Schweitzer, Marcel Dekker, 2003.
14. Introduction to Solids, L.V. Azaroff, Tata McGraw-Hill, Bombay, 1960.
15. Materials science and engineering: a first course, III Ed V. Raghavan, Prentice Hall of India, 1996.
16. Understanding materials science: history, properties, applications, R.E. Hummel, Springer Verlag, N.Y., 2004.
17. Crystal growth: processes and methods, P. Santhana Raghavan and P. Ramasamy, KRU Publications, Chennai.
18. Preparative methods in solid state chemistry, P. Hagenmuller, Academic, 1972.
19. Thin film deposition: principles and practice, D.L. Smith, McGraw-Hill, 1995.
20. Properties of materials, M.A. White, Oxford Univ. Press, 1999.

ELECTIVES COURSES

MS13: Corrosion Science and Engineering (30 Lecture Hrs)

Coordinators: Dr. S. Ningshen(ning@igcar.gov.in),
Shri M. V. Kuppusamy(masikuppu@igcar.gov.in)

Course Details:

- **Thermodynamics of Aqueous Corrosion:** Electrode processes – electrode potential, free energy, EMF series, potential measurements with reference electrodes, three electrode systems, computation and construction of Pourbaix diagrams of Fe, Al, Ni and Zn, practical use of E-pH diagrams. Chemical Vs electrochemical mechanisms of corrosion reactions, corrosion rate expressions.

- **Kinetics of Aqueous Corrosion:** Corrosion current density and corrosion rate, exchange current density. Polarization – activation control, Tafel equation, mass transport control, mixed potential theory and behavior of galvanic couples in acidic environments, effect of oxidizer, combined polarization, factors affecting polarizations and rate of corrosion. Passivity, potentiostatic polarization curves, factors affecting passivity, mechanism of action of passivators.

- **Forms of Corrosion**: General corrosion – atmospheric corrosion, galvanic corrosion, general biological corrosion. Localized corrosion – filiform corrosion, crevice corrosion, pitting corrosion, localized biological corrosion.

- Metallurgically influenced corrosion-inter granular corrosion, de-alloying. Mechanically assisted corrosion – erosion corrosion, fretting corrosion, corrosion fatigue. Environmentally induced cracking – mechanisms of stress corrosion cracking and hydrogen embittlement.

- **Corrosion in Reactor and Reprocessing Plants:** Corrosion in liquid sodium, cooling water, sea water; Corrosion in nitric acid – effect of flow, environment and metallurgical variables of materials.

- **Prevention and Control of Corrosion:** Corrosion control by design. Selection of corrosion resistant materials – alloying, stainless steel and brass. Oxidation resistant materials, control of high temperature oxidation. Cathodic and anodic protection methods. Use of inhibitors-types. Corrosion in cold water pipes – Langalier saturation index.

- **Corrosion Monitoring:** Introduction – On-stream monitoring – Electrical resistance, linear polarization, hydrogen test probe, ultrasonic testing, radiography and corrosion coupons. Off-stream monitoring equipments – Acoustic emission testing, eddy current inspection, liquid penetration inspection.

- **Corrosion Testing:** Purpose and classification. Dimensional charge – Ultrasonic thickness measurements, eddy current, microscopic examination. Weight charge – Specimen preparation, test conditions and evaluation of results for overall corrosion, SCC, IGC. Electrochemical techniques – Polarization curves, Tafel extrapolation, linear polarization, AC impedance methods (EIS).

Course Outcomes:

Students will develop the ability to analyze thermodynamics and kinetics of aqueous corrosion using electrode potentials, polarization behavior and Pourbaix diagrams. They will evaluate forms of corrosion, environmentally assisted cracking, corrosion in reactor and reprocessing systems, and apply corrosion monitoring, testing and prevention strategies.

References:

1. Herbert H. Uhlig and R.Winston Revie, “Corrosion and corrosion control – An introduction to corrosion science and engineering”, Third Edition, John Wiley & Sons, 1985.
2. Mars G. Fontana, “Corrosion Engineering”, Third Edition, Mc Graw Hill Inc., 1987.
3. D.A.Jones, Principles and prevention of corrosion, Second Edition, Prentice Hall Inc, 1996.
4. ASM hand book – Vol 13: Corrosion, ASM International, 2001.
5. Philip A. Schweitzer, “Corrosion and corrosion protection handbook”, USA, 1983.

MS14: Mechanical Behaviour of Engineering Materials (30 Lecture Hrs)

Coordinators: Dr. A.Nagesha
(nagesh@igcar.gov.in)

Course Details:

- **Engineering Materials:** Alloys, intermetallics, ceramics, composites, polymers.
- **Basic Crystal Structure of Materials:** Unit cell, packing fractions, planes and directions, slip systems
- **Defects in Materials:** Point defect, line defect (dislocation), surface defects (grain boundary, twins, stacking faults), volume defects
- **Dislocation:** Types, Burger's vector, stress field and energy, stacking faults, dislocation glide and slip systems in crystal, interaction between dislocations,interaction between dislocations and point defects, dislocation pile up, dislocation climb, dislocation sources, multiplication of dislocations.
- **Elastic Behaviour of Materials:** Stress and strain at a point and their relationship
- **Plastic Behaviour of Materials:**
- **Tensile Deformation:** single crystal, yield point, CRSS, polycrystalline materials
- (Schmidt's factor), grain size effect-Hall-Petch relation, thermally activated deformation, constitutive equation for plastic deformation, strain hardening and dynamic strain ageing (DSA).
- **Strengthening Mechanism:**Strain hardening, strengthening from grain boundary, solid-solution strengthening, order-disorder strengthening, precipitation strengthening, dispersion strengthening, strengthening by point defects, martenisitic strengthening, and composite materials.
- **Creep:** Creep curve, mechanisms of creep deformation, activation energy for creep deformation, structural changes during creep, deformation mechanism map, super plasticity, presentation of creep data, prediction of long-term creep properties, irradiation creep, grain boundary sliding, nucleation, growth and coalescence on inter granular cavities, effect of impurity segregation on cavitation, creep fracture of weld joint, design of creep deformation and fracture resistance materials.
- **Fatigue:** Types of loading, high cycle fatigue, low cycle fatigue, thermo-mechanical fatigue, creep-fatigue interaction, fretting fatigue and corrosion-fatigue of various engineering materials, effect of surface treatment and coating, fatigue behaviour of welds, characterization of fatigue deformation and damage, fatigue under combined stresses, notch sensitivity, design criterion, life prediction techniques, alloy design against fatigue.
- **Fracture Mechanics:** Ductile to brittle transition, Griffith's law, strain energy release rate, introduction to linear and non-linear fracture mechanics, fracture toughness, fatigue and creep crack growth, material design against fracture.

Course Outcomes:

This course enables students to understand elastic, plastic, creep, fatigue and fracture behavior of engineering materials based on crystal structure and dislocation mechanics. Students will apply strengthening mechanisms, fracture mechanics and life prediction concepts for materials design under mechanical, thermal and irradiation environments.

References:

1. Physical Metallurgy Principle – R. E. Reed-Hill
2. Modern Physical Metallurgy – R. E. Smallman
3. Mechanical Metallurgy – G. E. Dieter
4. Plastic Deformation of Metals – R. K. W. Honeycomb
5. Introduction to Creep – W. W. Evans
6. Fatigue of Materials - S. Suresh, CambridgeUniversity Press.
7. Deformation and Fracture Mechanics of Engineering Materials – R. W. Hertzberg

MS15: Manufacturing Technology (30 Lecture Hrs)

Coordinators: Dr. M. Vasudevan (dev@igcar.gov.in)

Course Details:

- **Nuclear materials and their melting practices:** Selection criteria for in-core, structural and steam generator materials, Radiation damage, Properties of nuclear materials. Principles of Vacuum melting & casting processes, including general descriptions of vacuum induction melting, vacuum arc re-melting and electro-slag refining.
- **Hot and cold working processes and tube making processes:** Fundamentals of mechanical processing, defects during manufacturing, Various techniques for producing seamless pipes, design of tooling for hot extrusion and principles of pilgering and various presses and their characteristics.
- **Special metal forming processes:** High velocity forming processes like explosive forming, pertroforge forming, electro magnetic and hydraulic forming, comparison of HVF methods, Super-plastic forming.
- **Powder metallurgy :** Introduction, characterization of metal powders. Manufacturing of metal and composite powders. Compaction and sintering of metal powders. Secondary operations. Applications of typical P/M components.
- **Computer aided design:** Role of computers in design and manufacture, Solid modeling– techniques and algorithms for modelling – data structures for solid models; Surface modeling – curves and surface representation – composite surfaces – application to computer aided manufacture; Current developments in CAD – feature based modeling – Design by feature – function, feature linkages – Application of feature based models. Parametric modeling.
- **Metal joining principles and processes:** Fusion and non- fusion welding processes, modern welding processes, design of welded joints, Introduction to residual stresses and distortion in welds.
- **Weldability of materials:** Welding of austenitic stainless steels, ferritic steels, weldability tests, dissimilar welding and selection of weld consumables and welding defects, principles of post weld heat treatment and stress relieving.
- **Welded Fabrication:** Codes and Standards, Procedure and performance Qualification, Evaluation of the welded joints, NDT of welds.
- **Hard facing Technology:** Introduction, Need for hard facing, Hard facing processes, Hard facing in nuclear power plants.
- **Heat Treatment:** Annealing, normalizing, quenching and tempering, Precipitation hardening, Recrystallisation annealing, Importance of heating and cooling rate and hold time in heat treatment, Heat Treatment furnaces.

Course Outcomes:

Students will gain competence in manufacturing and fabrication technologies relevant to nuclear and engineering materials, including melting, forming, powder metallurgy, welding and heat treatment. They will understand weldability, residual stresses, codes and standards, CAD/CAM principles, and specialized processes such as hard facing and vacuum melting.

References:

1. Metal Forming Handbook, Schuler, Springer Verlag, Berlin, 1998.
2. Welding Technology for Engineers, Baldev Raj, Shankar (V) And Bhaduri (A K), Narosa Publishing House, New Delhi, 2006.
3. Fundamentals of Metal Forming, Wagoner (R H), John Wiley & Sons, New York, 1997. 4.CAD/CAM from Principles To Practice, Chris Mcmahon And Jimmie Browne, Addison – Wesley, 1993.
4. Manufacturing Technology: Foundry, Forming And Welding, Rao (P N), Tata Mcgraw-Hill, New Delhi, 1987