REVIEW OF FAST REACTOR ACTIVITIES IN INDIA (1984)

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0. GENERAL BACKGROUND

0.1 The overall growth in national income in 1984-85 is anticipated to be of the order of 4 percent on top of 7.4 percent recorded in the previous year. Industrial production also recovered during the year and according to present indications, it may show a growth rate of about 7 percent in 1984-85. For the Sixth Plan as a whole, however, the growth rate in industry is likely to average about 6 percent. Power generation during the period April-December 1984 was 13.5 percent higher than in the same period of the previous year, as compared with an increase of 7.6 percent in 1983-84. Coal production increased by 6.9% during April-December 84 as compared with 5.8 percent in 1983-84. Inspite of the improvement in supply of energy in various forms, most regional grids continued to experience substantial power cuts. Demand for electrical energy is expected to continue to exceed the supply in the next fifteen to twenty years. As fossil fuels get utilised and become dearer, demand for nuclear energy is expected to grow at a fast pace.

0.2 After overcoming some teething problems, Madras Atomic Power Plant Unit 1 (MAPP-1) entered commercial production in January, 1984 and attained an availability factor of 75.3% and capacity factor of 64.3%. But for the limits placed on the bundle power and channel power during approach to an equilibrium core, capacity factor could have increased further by few points. Moreover, the generation cost per KWhr as determined by the established ground rules for determining financial charges (i.e. interest, depreciation and margin of profit etc) lead to lower values as compared to the cost of electricity generated by coal fired power stations. It may be recalled that MAPP-1 represents the first nuclear power plant built totally by Indian engineers and Indian industry. Significant progress was made in developing the remote repair technique for recommissioning Ranapratap Atomic Power Plant - Unit-1 and the unit already was recommissioned in early 1985. This has lead to a vastly improved climate for Nuclear Energy in India. A new site has been announced for construction of a two unit station near Karwar on the West Coast in Karnataka state while two more units have been also announced at the existing site at Ranapratap Sagar in Rajasthan. Government of India has also accepted "in principle" the 15 year profile of attaining an installed nuclear capacity of 10 million kilowatts. Consequently, it has been planned to commence work on 12 units of 235 MWe and 3 units of 500 MWe in the Seventh Five Year Plan (1985-1990).

0.3 Reactor Research Centre has continued to work at about the same level as last year. Total staff strength as on 31.3.84 is 1950 men amongst which one finds 530 scientists and engineers and 1000 technical personnel. Budget for the year 1985-86 is 188×10^6 Rupees as compared to the figure of 137×10^6 Rupees for the year 1984-85.

1. PROGRESS OF FAST BREEDER TEST REACTOR (FBTR) AT KALPAKKAM

1.1 During the year under review, construction activity has been practically completed as required for the 1st criticality of FBTR. The reactor is expected to become critical by middle of 1985. After attaining criticality, low power physics and shielding experiments will be conducted. The reactor will then be shut-down for few months to complete the complementary shielding and for preparations for raising the reactor power to obtain 60% of the power density. Some fuel subassemblies will then be withdrawn for post-irradiation examinations before obtaining clearance for operation at full power.

1.2 Commissioning tests are in progress. The progress of commissioning activity has been slower than anticipated due to difficulties encountered. One problem that had caused some significant delay was the existence of minor leaks in the primary argon cover gas system which surfaced during the "pressure hold test" before obtaining clearance for charging sodium. As in the case of Rapsodie, the leak tightness depends on the good sealing to be attained by a large number of O-ring seals in the top closure of reactor vessel, intermediate heat exchanger, sodium pumps etc. and some of them were leaking. The total leak was less than that from an equivalent circular opening of 0.8mm diameter. But due to inaccessibility of these openings fitted with O-rings it took a considerable time to finally locate the minor leaks, obtain the desired leak-tightness and to demonstrate that the balance unaccounted leak is not from the primary system into its double envelope but only from the cover gas space into "inter-seal" argon system. The problem has been solved.

1.3 There are one or two incidents which are perhaps worth mentioning. The first is related to a leak in the cold traps of the secondary sodium system. During preheating of the secondary sodium system, a leak of NaK alloy was observed. It may be recalled that NaK alloy is used as a thermal coupling between the sodium in the cold traps and an organic fluid which is used as a coolant. As a combination of a faulty design, inadequately detailed procedure and some neglect on the part of the operator, few litres of NaK spilled out and caught fire. The incident has been analysed. Design deficiency has been corrected. Proper procedure prepared and the cold traps have been recommissioned. The incident has been a blessing in disguise as certain weakness have been revealed during the commissioning phase itself before the primary sodium cold traps have become radio-active.

1.4 Another incident, has been in relation to Control Rod Drive Mechanism (CRDM). One of the mechanism was tested in hot sodium. At the end of the test, a permanent deformation of the mechanism resulting in a displacement of about 10 mm at the lower end (Gripper End) from its true position has been encountered. A detailed analysis appears to indicate that such a deformation can be explained only as a result of residual stress in the raw material and a non-uniform temperature distribution around the circumference of the container wall of the drive mechanism in a portion situated in the argon cover gas space between the free level of sodium and the underside of the rotating plugs through which the CRDM enters the reactor vessel. Fortunately, residual stress equal to the yield strength is required to explain the distortion observed and hence recurrence of the problem in the actual reactor due to deployment of other rods of the same batch of manufacture is not foreseen where smaller temperature gradients and better mechanical restraint is available at the guides of CRDMs. Apart from this, there is not much to report. The actual erection and final assembly has been well within the permissible limits and indeed we have been pleasantly surprised to find that we have been able to attain similar or better results than those reported in the Rapsodie documents related to final assembly.

1.5 Fuel for the reactor is mixed carbide of plutonium containing 70% PuC and balance UC. Initially, with the object of maintaining very low partial pressures of CO within the fuel pin, we had aimed to limit O_2 and N_2 impurities in the fuel to less than 1500 ppm. But due to inherent thermodynamic characteristics of such a fuel, it was difficult to attain the values set in the original specifications. But subsequent measurements of CO partial pressure measurement for the fuel has given very low values $\sim 10^{6}$ atm under operating temperatures expected for the fuel even for the higher concentration of O_2 observed. Hence the fuel has been accepted and now we await with hope the results of irradiation of this fuel in FBTR.

2. DESIGN STUDIES FOR PROTOTYPE FAST BREEDER REACTOR (PFBR)

In the last report to IWGFR, it was mentioned that a Preliminary Design Report on a 500 MWe Prototype Fast Breeder Reactor has been prepared. Due to preoccupation with the completion of construction of FBTR and its commissioning, it has not been possible to record sufficient progress in the detailed design of PFBR. Preliminary seismic design of the "Pool" and the inner vessel has been completed. The limited effort has been focussed on the design of key components like the sodium pumps, drives for sodium pumps, control rod drive mechanism and steam generators. Attention is now focussed on getting one prototype ready and to test it in the next 5 years. The engineering development figures in the Seventh Plan proposals and has been accepted "in principle" by the Government.

3. REACTOR PHYSICS STUDIES

3.1 Nuclear Data Evaluation processing and testing is a continuing activity in RRC. Determination of temperature derivative of the self shielding factor for U238, determination of Doppler coefficient using RRC set for comparison with SEFOR results, analysis of selected fast critical assemblies using recently generated ENDFB based cross-section data for structural materials can be cited as examples of the activities of this group engaged in Nuclear Data Evaluation. The group has also undertaken an IAEA contract for evaluation of Th232 and U233 data. Displacement cross-section data for structural materials has also been retrieved from DAMSIG library obtained from IAEA and has been used to prepare the plots of DPA in stainless steel at various axial and radial positions in FBTR. The results have been compared with those obtained from code package 'RECOIL'.

3.2 Following the decision to limit the critical mass of FBTR to a low value for the first criticality, the control rods were found to be lying on the boundary of the core and reflector. For this configuration detailed calculations have become necessary to obtain control rod worths, danger coefficients for fuel, coolant and structural materials and various temperature/power coefficients. These have been followed by the calculations to evolve the start-up procedure.

3.3 Study of noise transmission characteristics of non-multiplying media in LMFBRs using transport theory has been made.

3.4 Sodium boiling noise signals available from IAEA for analysis have been received and analysis of the signals has been initiated as a part of the coordinated research programme with IAEA.

3.5 Work pertaining to fission product decay power has been taken up to compare the results of theoretical estimates with experimental data from Japan.

3.6 It has been felt desirable to validate the design of the radiation shield internal to the pool of PFBR. Towards this end, an experiment is being planned at APSARA (a swimming pool reactor). The reactor will serve as a source of neutrons. Use of a convertor plate is contemplated to convert thermal neutrons into fast neutrons. Required calculations for determination of neutron transport in thick shields have been completed.

3.7 A programme to simulate fast neutron streaming through ducted shields has also been completed. The doubly differential Albedo data for concrete has been prepared. It is now being tested with a bench-mark experiment from ORNL.

4. RADIO-CHEMISTRY PROGRAMME

4.1 As a prelude to start of work on the mixed carbide material chosen as fuel for FBTR (Pu content 55 to 70%) for setting up the various equipments and developing techniques, work has been initiated on oxide systems. In this context, oxidation and phase studies in U-Ce-O system, thermal conductivity measurements at high temperature, oxygen potential measurements by gas equilibrium method, high temperature heat capacity measurements of zirconates of alkaline earth metals, precise lattice parameter measurements of Urania-Ceria-solid solutions and experimental determinations of vapour pressure by Knudsen Effusion target collection method have been initiated.

4.1.1 Oxidation & Phase Equilibrium: Systematic studies on the oxidation and phase behaviour of mixed uranium-cerium oxide solid solutions were taken up as a function of cerium content. Samples with different compositions were oxidised in air at various temperatures and the progress of the reaction followed by thermogravimetry. The initial O/M was determined by wet-chemical analysis and O/M reached at various stages of oxidation by thermogravimetry. Before and after oxidation at each temperature the phases were characterised by x-ray diffractometry. Lattice parameters of the products of oxidation were also calculated. These studies are in progress for varying ceria contents in the range 10-90 mole % in steps of 10 mole %. At each composition, the progress of the reaction was followed by thermogravimetry and the product of oxidation subjected to phase characterisation by x-ray diffraction. For y = 0.1 a single orthorhombic M_3O_8 type phase was observed. For $0.1 < y < 0.4$, oxidation has led to a mixture of $MO_2 + x^{fcc}$ phase and M_3O_8 orthorhombic phase. For $0.4 < y < 0.9$, a single $MO_2 + x^{fcc}$ phase was obtained. The lattice parameters for many of these oxidation products were measured and further investigations are in progress. It is planned to take up such studies upto 1600°C.

4.1.2 Thermal Conductivity Studies: Thermal conductivity studies have been carried out on polycrystaline thoria and uranium dioxide by Laser-Flash thermal conductivity apparatus. Temperature upto 1000°C have been reached.

4.1.3 Oxygen Potential Measurements: Oxygen potential measurements by gas equilibrium method have been carried out on Uranium Cerium oxide system upto 1273°K.

4.1.4 High Temperature Heat Capacity Measurements: High temperature enthalpy measurements have been carried out on (BaSr) ZrO3 upto 1700°K.

4.1.5 Thermal Expansion by High Temperature X-ray Diffractometry: Thermal expansion of platinum and alumina upto 1773°K and of europia upto 1273°K has been measured by high temperature x-ray diffractometry.

4.2 Process Chemistry

Studies on third phase formation in Pu(IV) - HNO_3-TBP system were continued. Data were obtained on the limiting concentration of Pu(IV) in 30% TBP in n-Dodecane at 25°C, as a function of equilibrium aqueous nitric acid concentration. Studies on isolation and identification of organic compounds formed during dissolution of uranium carbide in HNO_3 were continued. Different procedures for initial removal of uranium from the solution were attempted and it was found that ion exchange procedure was simple and effective. Studies on third phase formation in Pu(IV)-HNO_3-TBP system were continued with Dodecane replaced by Shellol-T as dilutant.

4.3 Carbon in Sodium

4.3.1 Development of electrochemical meters has been continued. Carbon meter has received considerable attention. The main problem hindering the use of electrochemical carbon meter for long term carbon activity measurement was the evaporative loss of sodium from the container. This problem was circumvented in a new design, wherein the evaporating sodium gets frozen at the cooler top end of the container and hence avoiding further evaporation.

4.3.2 The meter was used to measure the equilibrium carbon potential in sodium in contact with SS 304. The emf was found to be 170 ± 20 m.v. corresponding to a carbon activity of 5 x 10^5 which is in approximate agreement with the equilibrium carbon activity of $Cr_{23}C_6$.

4.3.3 The emf output was not very stable, when the carbon meter was used to measure 'C' activity in sodium. The inconsistency in the emf output, with commercial sodium was presumed to be due to various carbon bearing species present as impurities in sodium. Hence, pure sodium was prepared by distilling commercial sodium and collecting the distillate in an alumina crucible. Two meters are being tested with pure sodium.

4.3.4 The carbon activity in sodium in equilibrium with Cr-$Cr_{23}C_6$ was measured with the electrochemical carbon meter. Initial experiments gave an emf of 196 mV at 850K.

4.3.5 Carbon activity in sodium in equilibrium with SS 304 was measured both by foil equilibration and electrochemical carbon meter. There was good agreement between the two values at 936 K and 908 K. Measurements at other temperatures are in progress for both the above experiments.

4.3.6 Measurements on the solubility of cyanide in sodium under conditions of controlled carbon activity have been carried out in the temperature range 350-495°C.

4.4 Hydrogen in Sodium

The $CaCl_2$-CaH_2 based hydrogen meter for sodium coolant was tested in a sodium loop at a cold trap temperature of 139°C and various probe temperatures ranging from 360°C to 510°C. This was done to establish the concentration-temperatures regimes for this meter in which it can be used reliably. When the meter was started after a shut down, a period of conditioning was observed before the meter could give the theoretical output. An upper limit for probe temperature was also noticed around 500°C. Above this temperature considerable deviation from theoretical value was observed, indicating the onset of electronic conduction in the electrolyte. Repeated cyclings of the probe from 360°C-500°C showed reproducible and theoretical outputs.

5. METALLURGY PROGRAMME

5.1.1 Micro-structural Instability of Stainless Steel 316 at High Temperature (Weld Metal): One way of looking at this phenomenon is to carryout tensile tests at a nominal strain rate of 4×10^{-4}/sec on aged weld metal and determine true stress, true plastic strain and work hardening rate to obtain $\Delta\sigma$ which is defined as difference between $\sigma 0.10 - \sigma .002$ of the true stress strain curve. The results indicate that there is significant increase in the work-hardening at ageing temperature of 673°K and 973°K in contrast with 773°K. Duration of ageing is less effective in increasing the $\Delta\sigma$. Impact energy also decreased with increase in ageing temperature and time. This degradation is attributed to precipitation at the grain boundaries causing intergranular fracture.

5.1.2 Effect of Ageing on the Tensile and Impact Properties of AISI 316 Stainless Steel (Base Metal): This class of stainless steel shows dynamic strain ageing in the temperature range of 523-923K. Dynamic strain ageing is accompanied by a flow stress peak/plateau, work-hardening peak and a ductility minimum. An activation energy of 277 kJ mol^{-1} for the onset of serrated yielding is obtained. This supports the contention that diffusion of substantial elements, most likely chromium, could be responsible for dynamic strain ageing in this material. The precipitation behaviour is found to depend on the ageing temperature and time. Ageing at 823K and 923K shows an increase in the yield strength, while ageing at higher temperatures shows an opposite effect. The ductility parameters are found to decrease with an increase in the ageing temperature and time. The work-hardening behaviour of the material is not affected by thermal ageing. The impact energy decreased with an increase in ageing temperature and time. Embrittlement is caused by precipitation at grain boundaries and a consequent change from transgranular fibrous to an intergranular fibrous mode of fracture. The ratio P_{max}/P_{GY} is found to be a more sensitive indicator of embrittlement compared to the other parameters. An activation energy of 233 kJ mol^{-1} is required for embrittling process, which is similar to the activation energy needed for the diffusion of chromium in austenite leading to the conclusion that $Cr_{23}C_6$ carbide precipitation is the rate controlling mechanism.

5.2 Influence of Creep Damage on the Room Temperature Tensile Properties of Type 316 Stainless Steel

5.2.1 Room temperature tensile tests were carried out on samples with varying amounts of creep damage introduced in creep tests carried out at 650°C and stress level of 200 MPa and unloading the specimens at various fractions of the rupture life. The specimens were also creep tested after they were thermally aged at 650°C for 1000 h (The rupture life of the material was reduced by about half its value in the as received condition due to prior thermal ageing at 650°C for 1000 h). The following observations have been made in comparison with the results reported earlier on the as received material.

i) The yield strength and the ultimate tensile strength increased with increasing prior creep exposure time for the two different initial conditions of the material.

ii) At a given creep exposure time, there was no significant difference in the yield strengths of the material in the two different initial conditions, however the ultimate tensile strength of the material thermally aged prior to creep damage was found to be higher than that of the material without prior ageing.

iii) Percentage total elongation and the area under the tensile load elongation curve decrease with increasing creep time. Thermal ageing prior to creep reduces the values of both these parameters at a given creep time.

5.2.2 Interrupted creep tests on type 316 SS have been carried out at 750°C at 75 MPa and 550°C at 375 MPa to introduce possibly different types of creep damage in the material in the as received condition. Tensile results from samples creep tested at 750°C exhibited trends similar to those observed at 650°C. Creep tests at 550°C are in progress.

5.3 Sigma Phase and $M_{23}C_6$ Delta Ferrite Formation in Type 316 SS

5.3.1 Results of ageing at different temperatures (773°K, 873°K & 973°K) have been studied. It has been established that redissolution of delta ferrite phase starts after 250 hrs at 873°K and after 20 hrs at 973°K.

5.3.2 The amount of delta ferrite formed also appears to be a weak function of heat-input during welding.

5.4 Sensitization and Cold Work

5.4.1 Development of TTS Diagram for AVESTA Stainless Steel(304 SS): The time-temperature sensitization (TTS) diagrams for AVESTA 304 stainless steel have been obtained at different degrees of cold work ranging from 0-25% reduction in thickness. The presence of sensitization in heat treated samples was detected by using the intergranular corrosion test as per ASTM standard A262 practice E. It has been found that sensitization occurs only between 825-975K for mill annealed (0% CW) and cold worked materials. The nose temperatures was found to be about 900K and unaffected by cold work. However time to sensitization at nose temperature decreases with increase in cold work (0.8 h for 0% CW and 0.3 h for 25% CW).

5.4.2 Activation Energy for Sensitization in 316 SS: The activation energy for sensitization in type 316 stainless steel was determined at different degrees of cold work using the TTS diagrams developed previously by us. It has been found that in lower temperature range (825-925K) ln t Vs 1/T relation follows an Arrhenius type of behaviour (here t = time to sensitization (h) T = temperature (k). Slope of these linear plots remained same for all degrees of cold work. An activation energy of 232 kJ mol^{-1} was estimated from these plots. This activation energy compares well with the reported value of 246 kJ/mol for volume diffusion of Cr in austenitic stainless steels. Hence, the rate limiting step for sensitization at low temperature is the lattice diffusion of chromium.

5.4.3 Continuous Cooling Sensitization Diagram for Cold Worked 304 & 316 SS: Time-temperature-sensitization (TTS) diagrams provide data for selecting the optimum heat treatment conditions for avoiding sensitization in stainless steels. However these diagrams are less relevant to study sensitization produced during welding or continuous cooling/heating. For such applications, CCS diagrams are needed. Using the method developed at MDL, these diagrams have been constructed for Avesta type 304 and VIRGO 14 SB (type 316) stainless steels with prior cold work ranging from 0 to 25% reduction in thickness. From these diagrams critical linear cooling rates to avoid sensitization have been calculated for each cold work level and are shown in the following table:-

% CW	304 SS °C/h	316 SS °C/h
0 (as received)	138	367
5	222	710
10	329	763
15	333	516
20	278	815
25	248	792

5.5 Low Cycle Fatigue

5.5.1 Thermal Ageing and Low Cycle Fatigue in 304 SS: Solution annealed AISI 304 SS bars were given an ageing treatment at 823°K and 923K for 1000 hours, 3000 hours and 5000 hours. Samples fabricated from the exposed bars have been tested at 823K in axial strain control mode with a cyclic frequency of 0.1 Hz.

i) Prior ageing at 923K for 1000 hours has a beneficial effect on fatigue life at 823K at strain ranges less than 1.0%.

ii) Samples aged for 1000 hours have shown more amount of saturation hardening than the samples subjected to 3000 hours of thermal ageing.

iii) The fatigue resistance of samples aged for 1000 hours is higher than the samples treated at 923K for 3000 hours.

iv) LCF tests conducted at 823K at a frequency of 0.1 Hz 0.5 strain range showed that fatigue life for 5000 hr aged sample was intermediate to that of samples aged at 1000 hours and 3000 hours.

v) LCF tests were conducted at 923K on 5000 hours aged sample at a frequency of 0.1 Hz. Fatigue life was found to be better than that of samples aged for 1000 and 3000 hours. Metallographic examination of tested samples is under progress.

5.5.2 Stress Relief and Low Cycle Fatigue: Samples fabricated from weld joints (comprising of 304 SS base metal, 308 weld metal and heat affected zone) were given a stress relieving heat treatment at 1173K for 3 hours and then tested for its strain controlled low cycle fatigue properties at 823K with a ramp frequency of 0.1 Hz. The stress relieving heat treatment was found to improve the fatigue resistance. The failure in stress relieved joints has occurred in weld metal whereas failure occurred in the heat affected zone in the samples that are not subjected to stress relieving heat treatments.

5.5.3 Low Cycle Fatigue in PE-16 Super-alloy: A programme to study the low cycle fatigue properties of PE-16 super-alloy in solution annealed condition has been initiated. PE-16 rods were solution annealed at 1313K/4 h. Cylindrical samples of 25mm gauge length were subjected to LCF in total axial strain control mode. Samples were tested at a strain rate of $3.16 \times 10^{-3} sec^{-1}$, at 823 and 923 K and total strains varying from 0.5% to 20%. The main observations are

a) At 823K and 923K thematerial showed cyclic hardening in the first few cycles and saturation afterwards.

b) At 823K and 923K plastic strain range vs life was found to obey Coffin-Manson relationship.

c) At higher strain ranges DSA was present. DSA appeared in the form of serrations were more pronounced at 823K than at 923K. At 923K serrations disappeared after the first few cycles but at 823K it lasted for larger number of cycles.

d) With increase in temperature fatigue life decreased. Analysis of the test results are under progress.

5.5.4 Weld Flaws and Low Cycle Fatigue: A study has been initiated for assessing the significance of weld flaws on low cycle fatigue behaviour of manual metal arc austenitic stainless steel welds. Different types of flaws (porosity, slag inclusions, arc strikes etc) are being introduced into the weld metal by grossly exaggerating the conditions normally causing such flaws. Manual metal arc weld pads have been fabricated with slag inclusions and the characterisation of the flaw size and shape by non-destructive examination is under progress.

5.6 Creep and Creep Fatigue Interactions

5.6.1 Cold Work and Creep of 304 SS: The results of the creep tests conducted in air on solution annealed and prior cold worked 304 SS (5,10 and 20%) samples at 873K and 973K in the stress range of 120-300 MPa have indicated the following trends.

i) Rupture life decreases with increasing applied stress for a given level of PCW.

ii) Rupture life increases with increasing PCW at all stress levels in the range of stresses investigated.

iii) A drastic reduction in rupture ductility occurs at higher levels of PCW and at higher stresses.

iv) No significant change in rupture ductility has been observed in between solution annealed and PCW conditions at lower stresses (120 MPa).

v) The results at 973K are analysed and it is found that creep rupture lives are improved by four to five times after cold working. The ductility decreases with increase in cold work. Unlike solution annealed samples, it is found that there is no distinct steady state region for cold worked specimens. Instead minimum creep rate is observed and minimum creep rate decreases with increase in percentage of cold work.

vi) The results at 973K are analysed and it is found that the prior cold worked material does not show any distinct steady state creep region, unlike the solution annealed material. The cold worked material spends most of its life in the continuously increasing tertiary stage. Also, the empirical Monkman Grant relation (Relating rupture life and steady state creep rate) is found to be valid for both solution annealed and cold worked material.

5.6.2 Creep Tests of Virgo 14 SB: Creep rupture tests on heat E5158 VIRGO 14SB material are being carried out at 923K using multi-specimen creep rupture machine at stress levels of 100, 120, 150, 180 and 200 MPa. Specimens at stress levels of 180 and 200 MPa have already fractured yielding rupture times of 348 and 145 hours respectively. Specimens at a stress level of 150 MPa have ruptured with a rupture life of 1950 hours. Tests at 100 and 120 MPa are continuing with more than 2500 hours of creep time.

5.6.3 Creep Damage as Reflected in Room Temperature Tensile Tests on Type 316 SS: Tensile tests were performed on the samples machined from partially creep tested (200 MPa, 923K) companion specimens. The area under the tensile load-elongation curve has been determined as a measure of the toughness of the creep damaged material. The toughness was found to decrease by about 15% when the fraction of creep life time varied from 0.1 to 0.9. Another batch of specimens have been aged to different periods equal to the creep test time and were tested to study the possible differences in the tensile properties due to the presence of creep damage. The results of these tests can be concluded as:-

i) For a maximum exposure time of 200 hours (0.9 tr) the yield strength and U.T.S. increased approximately by 70 and 20% respectively over the values exhibited in the mill annealed condition.

ii) The corresponding decrease in the uniform elongation, total elongation and toughness (determined as the area under the stress-strain curve) was found to be 40, 40 and 30% respectively.

iii) Tensile tests carried out on samples thermally aged for durations equal to that of creep testing did not show appreciable variation in tensile properties compared with respect to mill annealed samples.

iv) Fracture occurred in predominantly intergranular mode on tensile testing the prior creep exposed samples.

5.6.4 Creep Fatigue Studies on 304 SS & Hold Time: Strain controlled low cycle fatigue tests were conducted on 304 SS at 923K with a ramp frequency of 0.1 Hz and hold times upto 10 minutes on samples solution treated to give 120 m grain sizes. The low cycle fatigue life results corresponding to a 20% decrease in tensile saturation stress are given below:-

ϵ_T %	ϵ_P %	Hold time (mts)	Number of cycles to failure (N_f)
0.8	0.75	0	2137
1.2	1.10	0	1480
1.6	1.50	0	1000
3.0	2.92	0	440
0.8	0.79	1	553
1.2	1.12	1	415
1.6	1.52	1	323
3.0	2.95	1	190
3.0	2.98	10	190

i) The above results for continuous cycling and 1 minute hold time tests have been found to obey the classical Coffin-Manson relationship, $\Delta \epsilon_p N_f^B$ = constant.

ii) The slope 'B' of log $\Delta\epsilon_p$ and log N_f plots for the hold time tests are very much higher (1.215) than that observed in continuous cycling condition (0.844). The severe degradation in fatigue life has been attributed to the interaction effects of creep fatigue and oxidation.

iii) Saturation in fatigue life degradation has been observed at longer dwell time (10 mts).

5.6.5 Creep Tests on FBTR Cladding Tubes: Creep tests on 20% cold worked clad tubes batch (No.749) at 923K and at a stress level of 80 MPa are under progress.

5.6.6 Metallographic Studies of Fracture Surfaces Produced in Creep Studies on 316 SS: The metallographic study of the creep fracture of AISI 316 stainless steel of different grain sizes (40,60,125,270 and 650μ) and temperatures (600°C and 700°C) is being carried out. The study involves the determination of crack orientation, maximum crack length, crack aspects ratio (crack length/crack width) and crack density (no. of cracks per unit area/no. of grains per unit area). The results obtained so far are as follows:

i) At 600°C, the crack orientation changes from parallel to the tensile direction to perpendicular to the tensile direction as the stress and grain size increase.

ii) At 600°C and different stress levels, creep ductility decreases with the ratio of maximum crack length to grain size, reaches a minimum value and then increases slightly.

iii) At 600°C crack aspect ratio increases with grain size at different stress levels, but at 700°C reaches a maximum value and then decreases.

6. REPROCESSING PROGRAMME

6.1 The programme is directed towards establishing a comprehensive set-up for reprocessing mixed carbide fuel containing high concentration of Plutonium in the mixed carbide (50 to 75%). Fuel subassemblies will be dismantled in the hot cells of Radio Metallurgy Laboratory of RRC to yield fuel pins while associated stainless steel hardware will be disposed of as high level solid waste. The pins are sheared into small pieces for head-end treatment to convert mixed carbide into mixed oxide. Next step is the dissolution and feed-clarification. This is followed by solvent extraction. Various equipments and auxiliaries have been developed and assembled inside cells to constitute a "single cycle".

6.2 Single Cycle

All the equipments inside this cell were commissioned. They are - dissolver, scrubbers (with scrub pots) evaporator (condenser) etc. All the tanks and metering air lifts were calibrated. Dissolver was run with water and the temperatures were measured. Process Cooling Water system was commissioned for all the jacketted vessels. Sparging system was commissioned. Some of the tanks in cell service area were calibrated with the single purge probe. Offgas system is functioning satisfactorily maintaining about 1.25" water gauge negative pressure in the vessels. Air pulsed mixer settler units are operating satisfactorily.

6.3 R & D Activities

6.3.1 Trough Contactor: Mass transfer were conducted with TBP/dodecane HNO_3 system with aqueous to organic flow ratio of 0.2 to 0.25 and number of theoretical stages were found to be between 5 and 8. Runs were conducted in round-the-clock shifts to test the reliability of systems and operation.

6.3.2 Sintered Filters: Extensive studies of the powder, filter element and suspension were made with scanning electron microscope and it was found that the performance deterioration of the filter was due to the irreversible migration of < 1μm particles.

6.3.3 Laboratory Mixer Settler: The units are functionally tested after some modifications. They are now tested for prolonged running.

6.3.4 Electrolytic Partitioning: Electrolytic reduction of Pu for partitioning is being carried out. New electrodes are being procured to decide the electrodes for plant scale purposes.

6.3.5 Equilibrium Data Collection: Analysis of samples from previous equilibrium experiments were completed. It is decided to perform mixer settler runs with Pu containing solutions for collecting equilibrium data. Preparations for this mixer settler experiments are in progress.

6.3.6 Single Stage Air Pulsed Mixer Settler: The equipment is working satisfactorily even with O/A ratio of 10 with 6 lph throughput. This is being tested with NaOH, simulating solvent wash conditions.

6.3.7 Electrolytic Dissolution: About a kilogram amount of UC pellets were dissolved in the one litre capacity electrolytic dissolver-cum-conditioner, for subsequent studies with the resultant solution to observe if there is any emulsification or other extraction problem during mixer settler operation.

6.3.8 Single State Air Pulsed Mixer Settler: Mass transfer runs with nitric acid - 30% TBP were highly satisfactory. This unit along with pneumatic interface control was handed over to the single cycle operation group for evaluating its reliability in the system.

6.3.9 16 Stage Perspex Lab Mixer Settler Unit: Arrangements were made to commission the glove box for flowsheet runs with the mixer settler unit. The unit was set up with the associated systems in the box. With the experience gained in this unit, a 7 stage mixer settler design was made and preliminary drawings were prepared.

6.3.10 Mini Air Pulsed Mixer Settler: One 8 stage unit was assembled, preliminary runs were satisfactory. Hydraulic steady state was observed upto a maximum throughout of 2 lph.

7. SAFETY RESEARCH

7.1 Influence of the atmospheric moisture content on the self-ignition behaviour of molten sodium in pool form was investigated experimentally. The ignition temperature was found to decrease with increasing humidity of the atmosphere contrary to earlier data available. Size characteristics of the smoke particles generated by fires of sodium containing radioactivity were studied. The fires were conducted under controlled conditions. The coagulation and settling behaviour of the smoke particles was also evaluated in the experiments conducted.

7.2 In the context of fuel coolant interaction studies, uranium dioxide pellets enclosed in ceramic sleeves were molten under water. Transient pressure pulses and the extent of fuel fragmentation produced were measured in the experiments in order to assess the thermal interaction potential. Scoping studies on thermal interaction between molten uranium carbide and sodium were carried out in an experimental set up assembled for the purpose.

7.3 A portable aerosol monitor based on light scattering principle has been designed and fabricated. The monitor is insensitive to ambient light, highly sensitive to aerosols and is quite useful for applications such as monitoring of dust and smoke in working environment.

7.4 As part of the personnel monitoring programme for assessing body burdens of radiation workers, whole body and lung counters have been installed in a special steel room. Intercomparison experiments for calibration of lung counter were carried out using a chest phantom consisting of plutonium and Americium loaded organs supplied by IAEA. A Research Coordination Meeting sponsored by IAEA on 'Calibration of Actinides Lung Monitor' was conducted.

7.5 In radiation physics, based on extensive transport theoretic computations, the limitations in the presently used absorptions co-efficients in gamma ray dosimetry are brought out and the appropriate coefficients have been suggested. As a part of ANS project on Gamma ray Standard, accurate shielding data for water, iron, lead, molybdenum tin and uranium have been generated. Measurements on the bremsstrahlung radiation in lead, copper and cadmium due to Sr^{90}- Yr^{90} beta radiation was measured and compared with the recent theoretical models. Effect of rare earth oxides in the structural material on the criticality for the fuel storage assemblies has been studied and it is shown that about 350 ppm of Gadolinium oxide in the structural steel can increase the fuel storage capacity by 30%.