Metallurgy Department. Progress report for the period 1 January to 31 December 1975

Forskningscenter Risø, Roskilde

Publication date:
1976

Document Version
Publisher's PDF, also known as Version of record

Risø Report No. 340

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Danish Atomic Energy Commission

Research Establishment Risø

Metallurgy Department Progress Report

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March 1976

Sales distributors: Jul. Gjellerup, 87, Sølvgade, DK-1307 Copenhagen K, Denmark

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UDC 669

March 1976 Risø Report No. 340

Danish Atomic Energy Commission
Research Establishment Risø

METALLURGY DEPARTMENT
PROGRESS REPORT

for the Period 1 January to 31 December 1975

ABSTRACT

The activities of the Metallurgy Department at Risø during 1975 are described. The work is presented in four chapters: General Materials Research, Technology and Materials Development, Fuel Elements, and Non-Destructive Testing. Furthermore, a survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff during 1975 is included.

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ISBN 87 550 0379 6

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INTRODUCTION

A political decision about the establishment of nuclear power stations in Denmark is expected in 1976 and preparatory studies were carried on throughout 1975. The Department participated in such studies together with industry, utilities and safety authorities. Staff members were also actively engaged in an information campaign relating to the use of nuclear energy in Denmark.

The more realistic plans for the introduction of nuclear power in this country have to a certain extent reorientated the work of the Department towards safety problems; contract work for the nuclear safety authorities is expected in this field in the coming years. The main technical areas in which we expect to be involved are: fuel elements, pressure vessels, material problems in general, water chemistry and non-destructive testing and control.

Together with these safety-orientated studies, the traditional programmes of the department were continued within such areas ofnuclear

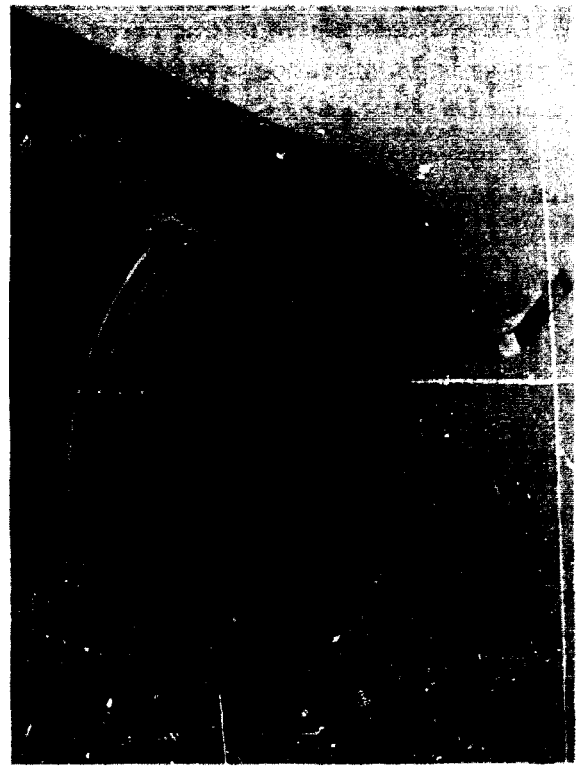

Fig. 1. The arrangement of the concentric fuel tubes in the tubular U-Al fuel elements for the Risø research reactor DR 3.

technology as the design and fabrication of fuel elements, in- and out-pile testing, post-irradiation examinations, and non-destructive testing of nuclear components. To supplement these programmes, work was done in the field of general materials research, including studies of mechanical properties, structure, radiation damage, and corrosion.

In the present report this work is presented in four chapters: General Materials Research, Technology and Materials Development, Fuel Elements, and Non-destructive Testing.

Work was also done under contract for industries and utilities in Denmark and abroad. Due to their proprietary nature, most of these activities are excluded from the present report. One of the projects successfully completed was a fabrication route for tubular uranium-aluminium fuel elements for test reactors. As a result, Elsinore Shipyard, who participated in the project, could conclude a contract for the supply of elements for the DR 3 reactor at Risø. Other projects were centered on the development of materials and processes, in particular a number of problems related to brazing were solved. Post-irradiation examinations of irradiated materials and fuels were continued; much effort was devoted to the examination of full-scale power reactor fuel rods ($Zr-UO_2$ and $Zr-UO_2-PuO_2$). As a new area, non-destructive testing based on acoustic emission techniques was taken up in collaboration with the Danish Welding Institute. Two senior staff members acted as part-time consultants to specific companies. A license agreement about the production and sale of an air gauge, developed in collaboration with the Danish Welding Institute for rapid determination of the internal diameter of tubes, was concluded.

The Department participated in international collaboration in a number of areas, for instance, fuel element modelling, materials development and examination, and safety analysis. Furthermore, we are represented in a number of international projects and study groups under the auspices of the NEA, IAEA, EEC and Nordic organisations.

Educational activities were continued, students and post-graduate research workers from Denmark and abroad studied in the Department. Two lic. techn. (Ph.D.) students passed their final examinations during the year, and the degree of dr. techn. was conferred on a staff member. Two members of staff received the Dr. Rene Wassermann Award from the American Welding Society, for the best article about brazing published in the Welding Journal during 1974.

GENERAL MATERIALS RESEARCH

Projects within the field of General Materials Research covered different aspects of mechanical properties and irradiation behaviour. Structural investigations were made with the purpose of relating the structure to the macroscopical behaviour of the materials.

Dislocations in Sapphire (In collaboration with the Department of Metallurgy and Materials Science, Oxford University, and with the Laboratory of Applied Physics I, Technical University of Denmark).

The structure of dislocations in deformed sapphire was investigated by weak beam electron microscopy. Some of the $\langle 01\bar{1}0 \rangle$ dislocations were dissociated into three $\frac{1}{3}\langle 01\bar{1}0 \rangle$ partials. The energy of the electrostatic faults between partial $\frac{1}{3}\langle 01\bar{1}0 \rangle$ dislocations on the prismatic slip planes was measured to $320 \pm 60\ mJ/m^2$. A faulted dipole was observed, and a mechanism for the formation of such dipoles was formulated (see fig. 2). Computer simulations support the interpretation of the electron micrographs.

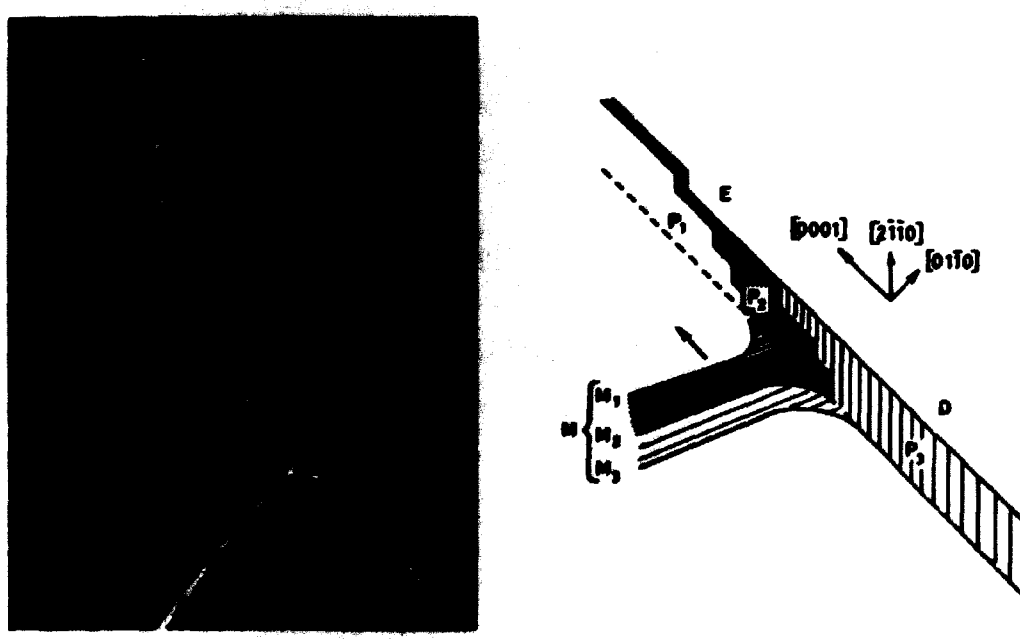

Fig. 2. Formation of a faulted dipole in Al_2O_3. The configuration consists of a mixed (predominantly screw) dislocation segment, M, dissociated into three $\frac{1}{3}[01\bar{1}0]$ partials, a constricted edge segment, E, consisting of three half planes (P_1, P_2, and P_3), and a faulted dipole, D. The mixed segment has been gliding in the direction indicated by the arrow.

Recrystallization in Dispersion-Hardened Metals

Experiments on the recrystallization of Al (99.5% purity) and Al with Al_2O_3 particles were carried out with special emphasis on the nucleation process. The parameters investigated were: degree of deformation, annealing temperature, particle size, and particle spacing. The nucleation of a recrystallized grain is shown in fig. 3.

Fig. 3. Recrystallization nucleus at $FeAl_3$-particle in Al - 0.75 w/o Al_2O_3, cold drawn 50% and heat-treated 1 hour at 340 °C.

The Dependence of Flow Stress on Grain Size in Aluminium

The effect of grain size on the yield stress (0.2% offset) and the flow stress (at larger strains) was studied for pure Al (99.999%). The Petch-relation

$$\sigma = \sigma_o + k \cdot d^{-1/2}$$

was confirmed for grain sizes between 30 and 1200 μm. The constant k increases with strain through a maximum at about 20% strain. At low strain values, k is approximately proportional to the square root of the strain.

Radiation damage in Stainless Steel (In collaboration with the Metallurgy Division, A.E.R.E., Harwell)

A new theory for void nucleation was developed in terms of Brownian motion of vacancy-gas atom complexes (i.e. void embryos). As these void

embryos describe Brownian motion, they collide with each other and coalesce. Consequently the number density of embryos decreases and the average embryo size increases. While these embryos migrate and coalesce, they grow also by the accumulation of vacancies due to the prevailing vacancy flux supersaturation. When the embryos have grown beyond their critical size for stabilization against thermal shrinkage and become spatially stable, the current void number density is taken to represent the final scale of nucleation.

The effects of damage rate, gas concentration and dislocation density on the scale of void nucleation were calculated for an austenitic stainless steel under irradiation at 600 °C in a high voltage electron microscope. The predicted number densities were found to be in good agreement with experimental results on 20Cr-20Ni and type 316 stainless steels. The calculated results were also consistent with experimental data reported for stainless steels irradiated in accelerators.

Radiation and Annealing of Copper (In collaboration with the Metallurgy Division, A. E. R. E., Harwell)

Specimens of copper were irradiated at low temperature (50 - 60°C) and subsequently annealed at various temperatures. Positron annihilation experiments were carried out; they suggest the existence of small voids.

Radiation Experiments in Copper-Nickel Alloys (In collaboration with the Metallurgy Division, A. E. R. E., Harwell)

Irradiation experiments on Cu-Ni alloys with 1-20 w/o Ni were carried out in a high voltage electron microscope at temperatures from 250 to 600 °C. Dislocation climb sources emitting interstitial loops were observed to operate (see fig. 4). The loops emitted were of three types, rectangular loops with Burgers vector a ⟨100⟩, habit plane {100} and line vectors ⟨011⟩, normal prismatic loops with Burgers vector $\frac{a}{2}$ ⟨110⟩, and Frank loops with Burgers vector $\frac{a}{3}$ ⟨111⟩. The observations suggest that the sources are platelets of Ni atoms on {100} planes.

Void formation and growth during electron irradiation was also studied in the Cu - Ni alloys. The growth rate of the voids was found to decrease with increasing Ni-content.

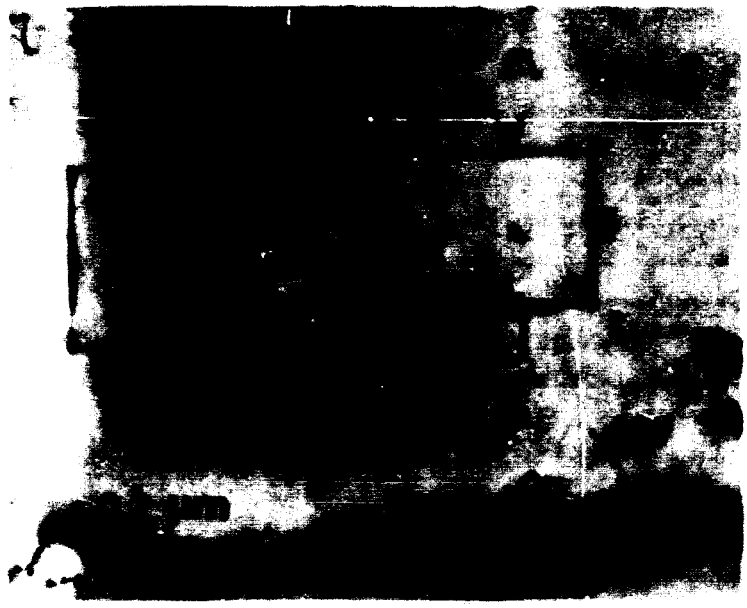

Fig. 4. "Rectangular" loops emitted from dislocation climb sources in Cu-10% Ni irradiated in a high voltage electron microscope with 1 MeV electrons at 350 °C ({100} approximately perpendicular to the electron beam). A small loop is forming inside another loop at one of the sources.

Oxides

The structures of non-stoichiometric cerium oxides were studied. The cerium oxide is considered to be a model material for plutonium oxide. Single crystals were annealed to reduce them to a non-stoichiometric composition (CeO_{2-x}). In one series of experiments specimens were annealed in a vacuum furnace and then investigated by electron microscopy; in another series annealing took place inside the microscope itself by beam heating. During the former (long-time) annealing process twins were formed, while during the latter annealing (of very short duration) structures formed by crystallographic shear were observed. Furthermore, superlattices were formed from the shear structures.

Thermal Analysis

For accurate control of the atmospheres used in thermogravimetric measurements a solid electrolyte $ZrO_2(CaO)$ cell was constructed. The principle of this cell is shown schematically in fig. 5.

The cell operates in the following way: Provided that the conductivity of the electrolyte is entirely ionic, the electromotive force for an oxygen cell can be expressed by

$$E = \frac{RT}{4F} \ln p''_{O_2}/p'_{O_2}$$

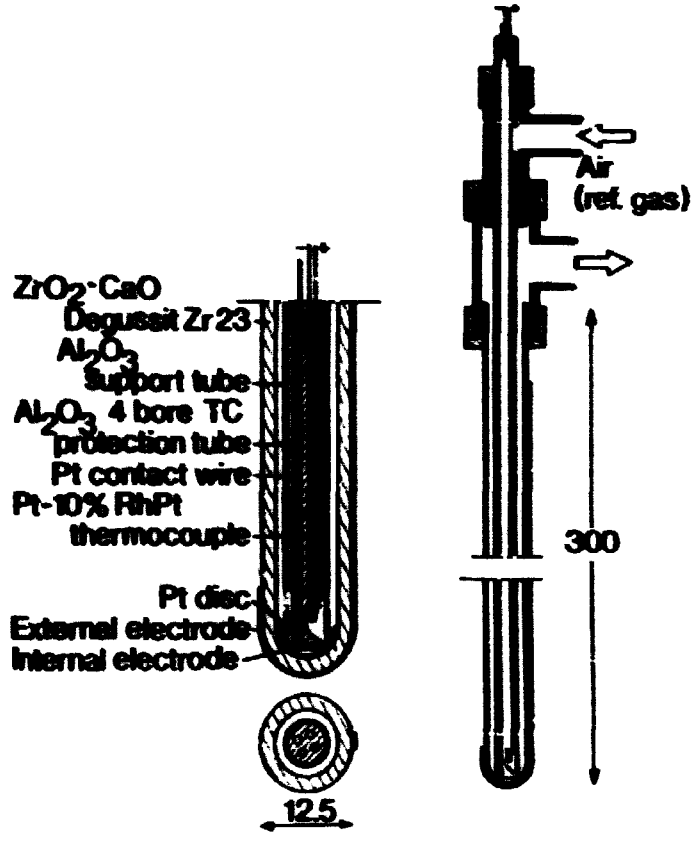

Fig. 5. Principle of solid electrolyte ZrO_2 (CaO) cell for measurements of oxygen pressures.

were F is the Faraday equivalent and p''_{O_2} and p'_{O_2} are the internal and external oxygen pressures, respectively. At a fixed temperature a linear relationship thus exists between E and $\ln p''_{O_2}/p'_{O_2}$. If for instance p''_{O_2} is kept constant by a continuous supply of a reference gas (air) inside the cell, the oxygen pressure of an atmosphere flowing outside the cell can be determined by measuring the emf of the cell. The cell, which operates at a fixed temperature of 1000°C, was calibrated with CO/CO_2 mixtures of well defined compositions.

Acoustic Emission in Steels

Equipment was completed to record, store and analyse acoustic signals. Two steels (with low and high carbon content) with pearlitic structure were tensile tested and the acoustic emission recorded. Acoustic signals seem to be correlated with dislocation movement; a possible correlation with cementite cracking is being studied. Acoustic emission dur-

ing cracking of a fully brittle material was studied with glass specimens with the aim of establishing a correlation between fracture energy and acoustic emission.

Dislocation Structures during Creep

A model for the period with zero creep following a stress reduction (the incubation period) was developed. The model is based on recovery phenomena in the dislocation structure. The calculated incubation times show good agreement with experimental data from the literature.

Irradiation and Mechanical Properties

The requirements to a rig for creep experiments during irradiation conditions were established. Nickel is to be used as a model material.

A study was made of the effect of irradiation on the tensile properties of single crystals of Cu, Cu with Al in solid solution and Cu dispersion-hardened with Al_2O_3.

Creep in Dispersion-Hardened Metals (In collaboration with Battelle Columbus Laboratories, Columbus)

The creep experiments on the Al-Al_2O_3 system were completed with data for long times and low stresses, and supplemented with tensile tests at high temperature. Materials with different particle spacings were investigated. The experimental data could be described by the empirical equation

$$\frac{\sigma}{G} = 0.75 \cdot 10^{-4} \log\dot{\varepsilon} + 0.8\, T^{-1} + 1.8 \cdot 10^{-4}\, D^{-1} - 1.7 \cdot 10^{-4}$$

where σ is the applied stress, G the shear modulus, $\dot{\varepsilon}$ the creep rate, T the temperature in K, and D the particle spacing. An attempt was made to correlate this empirical equation with models based on dislocation climb at particles.

Work Hardening in Fibre Composites

The work hardening of composites was studied in the model system Cu with W fibres. From tension-compression tests it was possible to identify two contributions to the work hardening: the contribution from the non-zero mean stress from the geometrically necessary dislocations at the fibres, and the contribution from the reduced mean free spacing between the fibres caused by the accumulated dislocations. Tests at -196°C showed good

agreement with a theoretical model, while experiments at room temperature gave values lower than predicted. This is explained by a relaxation of the dislocation structures.

Creep in Fibre Composites

Creep experiments were conducted on Cu-W composites with a volume fraction of 25% of fibres with aspect ratios of 25 and 75. The results were found to be in reasonable agreement with known theories. A more general theory was developed, and a relation between the matrix creep behaviour and the composite creep behaviour was established and used to analyze the experimental data from Cu-W composites.

Plastic with Carbon Fibres

Investigations were made of joining methods for plastic reinforced with carbon fibres. Adhesive bonding is possible, but requires clean joining surfaces. Holes for bolting were loaded to local compressive failure in pin-and-hole experiments; the tightened bolts reduced the risk of failure. Machining of plastic with carbon fibres is generally difficult because of wear of the machining tools.

Additive Strength Contributions

These studies were continued with experiments on Cu with grain boundaries and dispersed particles (Al_2O_3). Specimens with well defined structural parameters were fabricated.

TECHNOLOGY AND MATERIALS DEVELOPMENT

Projects in this field were concerned with development and examination of materials and techniques with relevance to nuclear safety, nuclear energy, or non-nuclear industrial application. The nuclear projects were concentrated on Inconel and Zirconium alloys.

Creep of Dispersion-Strengthened Zirconium Alloys (In collaboration with Atomic Energy of Canada, Ltd.)

A number of specimens with 5 w/o Y_2O_3 in zircaloy-2 were irradiated at 300°C and 45°C in a fast neutron flux of $2.0 \cdot 10^{17}$ $m^{-2}s^{-1}$ and $1.5 \cdot 10^{17}$ $m^{-2}s^{-1}$, respectively. A comparison with results from other zircaloy-2 specimens tested simultaneously showed no large effect of the Y_2O_3 dispersion after the first 4000 h. The tests continue.

Incompatibility of Zircaloy-2 and Inconel X750 during Temperature Transients

The incompatibility of zircaloy-2 and Inconel X750 was investigated at 1000 to 1200°C. The result indicated that zirconium oxide can limit the extent of the reaction between zircaloy-2 and Inconel X750 at temperatures up to 1200°C, which is the maximum allowable cladding temperature used in the acceptance criteria for emergency core cooling systems in water reactors. The influence of oxide thickness and temperature is illustrated in fig. 6.

Measurement of the Ultrasonic Effect in an Ultrasonic Solder Bath

The technique developed for measuring the ultrasonic effect in a solder bath during the actual soldering was further refined.

Measurements showed that the ultrasonic effect depends heavily on the length of the transmitting ultrasonic horn, on the chemical composition of the solder, and on the distance from the transmitting horn. Furthermore, the effect was found to be independent of the temperature of the solder bath. A method was developed to produce ultrasonic horns with increased lifetime.

Nickel-Braced Inconel

Investigations were continued into the application of zirconium getters to the vacuum-brazing of Cr-Fe-Ni alloys containing small amounts of aluminium and titanium. Specimens were brazed using a Ni-10P and a Ni-13Cr-10P filler metal. They will be tensile-tested at room temperature and elevated temperatures in order to examine the strength of the brazed joints.

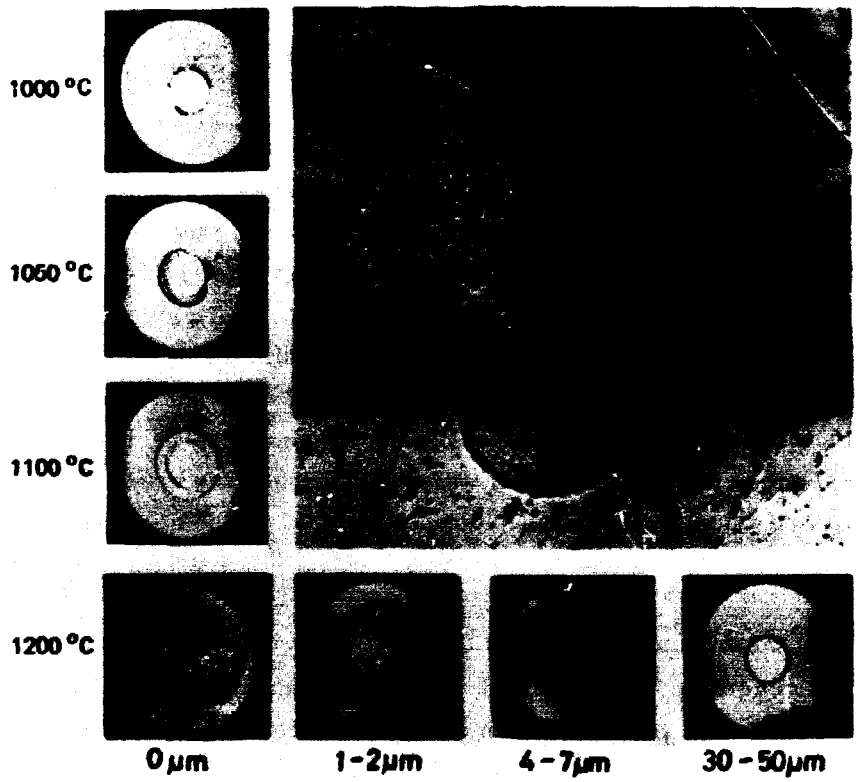

Fig. 6. The four photos to the left indicate the extent of the reaction between zircaloy-2 and Inconel X750 at temperatures from 1000 to 1200 °C (no oxide layer on the zircaloy), while the bottom photos illustrate the effect of oxide layers of different thicknesses on the reaction at 1200 °C. The larger photo is a detail from the top left-hand specimen and shows an incipient reaction with nickel diffusing into zircaloy (large hemisphere) and zirconium diffusing into Inconel X750 (small hemisphere).

Hydrogen Analysis

An apparatus was constructed for determination of hydrogen in metals by solid state extraction. The working principle of the apparatus is based on the application of semipermeable membranes of Pd-alloys.

A new model with increased capacity and higher maximum extraction temperature is under construction.

Corrosion of Zirconium Alloys

A series of examinations of the corrosion resistance of zirconium alloys embodied by the SCANUK programme[x] was terminated. The experiments comprised in-pile testing at 290°C in water and saturated steam, and at 400 and 500°C in superheated steam.

[x] Risø Report No. 327 (1975) p. 11

The main conclusion of the work is that most of the SCANUK alloys[x] have acceptable corrosion resistance under the given conditions.

Crack Propagation from Brittle to Tough Steel

The Dynamic Fracture Mechanics study of crack propagation was continued. The test specimens consisted of a tough mild steel brazed or electron-beam welded to a brittle steel in which a deep notch had been machined to act as a crack initiator. The specimen loading conditions were such that the influence of the machine compliance was eliminated. The energy available for crack propagation was thus only the elastic energy stored in the test piece which in turn was controlled by the geometry of the notch. The crack extension in the tough steel was observed, and the crack propagation was followed using an electrically conducting grid on the surface of the test piece.

Tensile Testing without Extensometer

It is generally assumed that an accurate description of the stress-strain behaviour of a material can only be obtained using an extensometer. The disadvantages of this method are that extensometers usually have rather limited maximum strains and that they cannot be used effectively at elevated temperatures. A procedure was worked out for the transformation of the cross-head movement to a proper strain (correcting for specimen misalignment, machine deflection, and take-up extension); the procedure is incorporated in the tensile-data computer code. The procedure was checked by testing twenty identical specimens in a 10 ton Instron, ten with extensometers, and ten with the use of corrected cross-head movement. The true-stress/true-plastic-strain curves obtained from these tests were then compared, with the following results:

- All twenty curves fell in one scatter band.
- The difference between the statistical mean curve for extensometer tests and the curve for "cross-head" tests was approximately an order of magnitude less than the spread around either of the means.
- Despite the fact that no correction was included in the "cross-head" tests to take account of the imprecise definition of the original specimen gauge length, there was no significant difference between the standard deviation of the two mean curves.

(x) Risø Report No. 327 (1975) p. 11

FUEL ELEMENTS

The manufacture of Danish fuel elements for the Halden and Kahl reactors has established an important part of the basis for future industrial fabrication of fuel in Denmark. Several Halden fuel elements have with satisfactory operation reached burn-ups comparable to those typical of power reactors.

In test fuel irradiations at Risø, higher burn-up rates are possible, and operating conditions in power reactor fuel pins can be simulated in a well-controlled manner. This provides verification of material and design parameters at high burn-ups, experimental data on failure mechanisms, and results for verification of fuel performance codes.

As a result of international collaboration, additional data will be available on fuel performance under normal as well as accident conditions. Examples of such collaboration arrangements are: the OECD Halden Reactor Project (Norway), the "Interramp" project at Studsvik (Sweden), the information exchange with NRC (USA), and the EEC sponsored activities (Brussels) related to Pu recycling in LWRs.

Danish UO_2-Zr Irradiations in the Halden Reactor

Irradiation was continued of five Danish fuel elements in the Halden reactor (Norway) and the following average burn-ups were achieved:

IFA No.	148	161	165	201	202
MWD/t UO_2	29,400	34,400	29,500	19,700	16,200

The max. local burn-up of 43,000 MWD/t UO_2 was obtained with IFA 161.

One element (IFA 164) with pellet and vipac fuel pins was unloaded early in 1975 at a burn-up of 20,600 MWD/t UO_2 and transported to the Risø hot cells. After non-destructive examination, one vipac and one pellet pin were ramp tested in the DR 3 reactor at Risø.

Danish Fuel-Element Irradiations in the Kahl Reactor

Four Danish UO_2-Zr fuel elements were loaded into the German power reactor in Kahl (BWR) in May 1975. They have now achieved an estimated average burn-up level of 2,300 MWD/t UO_2.

At Risø, a procedure was established for regular processing of the operational data from Kahl. This procedure makes it possible to evaluate the variations in the local heat loads of the fuel pins and any consequences of such changes.

Two short test-fuel-pins manufactured from the same UO_2 and Zr materials as the Kahl fuel pins are being irradiated at Risø and have now reached a burn-up of 16,300 MWD/t UO_2.

UO_2-Zr Irradiations at Risø

A number of fuel pins are being tested in the DR 3 reactor at Risø, some for verification of material and design parameters at high burn-up, and some in experiments simulating power reactor operating conditions. Selected results from these irradiations are used in the verification of Danish fuel performance codes.

Standard test pins have reached burn-ups of 36,000 MWD/t UO_2 for BWR- and 24,000 MWD/t UO_2 for PWR-type pins.

Several BWR-type pins irradiated to burn-ups in the range 20,000-40,000 MWD/t UO_2 were ramp-tested. They included a vipac and a pellet pin from one of the Danish Halden fuel elements. Detailed metallographic evaluation continued of medium burn-up fuel pins previously ramp-tested.

A facility with a movable absorber sleeve around a fuel pin was commissioned for load-following studies. Feasibility studies were completed for a facility with BF_3 absorber gas. Such a facility will increase the range of experimental conditions in ramp tests and load-following simulation.

Low-Interaction UO_2 Pellet Design

In order to reduce the consequences of pellet-clad interaction in UO_2-Zr fuel pins, a new pellet was designed. The pellet has a core of lower enrichment than the outer annular part (see fig. 7.). Computer model evaluations indicated significant improvements compared to the traditional pellet type. Preparations are now being made for experimental verification of the design by irradiation at Risø of a series of test fuel pins.

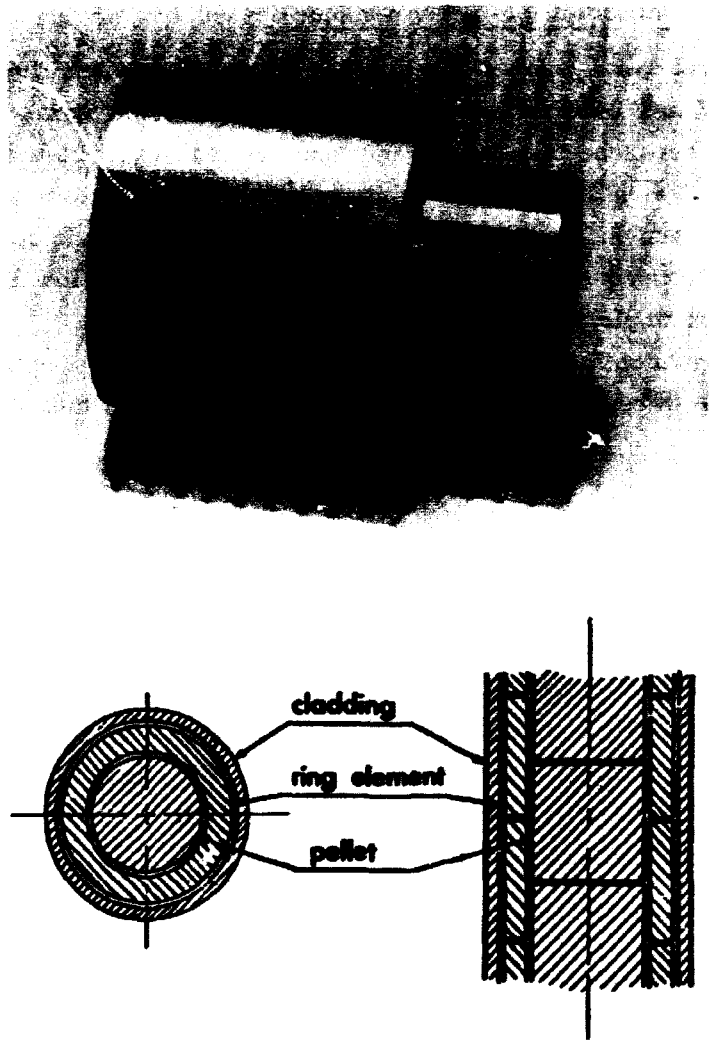

Fig. 7. The new pellet design.

Post-Irradiation Examination Methods

A new test bench for γ-scanning, γ-spectrometry, γ-densitometry, and profilometry of fuel pins was constructed. It is now being tested in the hot-cell workshop. The equipment will be capable of detailed digital recording of the various measurements with the exact axial and circumferential locations.

A data system to collect and handle the information from this test bench, and to operate the bench automatically, is at the commissioning stage.

The neutron radiography facility at the DR 1 reactor was expanded to accept fuel pins up to 4.5 m in length.

Computer Modelling of Fuel Performance

The first version (WAFER-1) of the three-dimensional fuel performance model was used for analysis of UO_2-Zr ramp test data. Reasonable agreement between calculation and experiment was obtained for clad stresses and strains. The calculations also showed that the pellet model needs improvement. It is also desirable to improve certain computational features. Consequently, specifications were prepared for a WAFER-2 version to be implemented during 1976.

In order to obtain relevant in-pile creep data for Zr cladding, various rig designs were examined in preparation for in-pile measurements at Risø.

NON-DESTRUCTIVE TESTING

Non-destructive testing techniques are important tools in the investigation of materials and structures. Through the improvement of existing methods and the implementation of new techniques, the projects described below contribute to the application of non-destructive testing in nuclear components control and in post-irradiation examinations.

X-Ray Control

As an extension of X-ray control methods, the use was adopted of X-ray paper instead of films. Densitometric evaluation of the radiographs showed that their quality is comparable to that of X-ray films. The technique is currently used for the determination of the uranium distribution in fuel plates for test reactors.

Acoustic Emission

The use of the acoustic emission technique for on-power control of steam pipes and feed-water reservoirs at conventional power stations involves special problems. The problems arise from cavitation noise from the feed-water pumps and from the very high temperatures at the pipe surfaces. The possibility of avoiding these disturbances was studied.

Tube Inspection (In collaboration with the Elsinore Shipyard, Ltd.)

The tube inspection system developed by the Department was further improved. It appeared that the lenses used for the ultrasonic transducers loosened during operation and gradually disturbed the transmitted signals.

The problem was solved by changing to a new type of transducer with the lenses mounted in a different way. Moreover, the stability of the water temperature was improved through a better cooling and circulating system. The wh le system is now working with a high degree of stability.

Neutron Radiography, Application

Irradiated fuel pins are now by routine neutron radiographed at the DR 1 facility at Risø. The radiographs have proved to be very useful in post-irradiation examinations because fuel pin areas of special interest can be localized. Furthermore, the radiographs also contain information that can be directly evaluated, such as dimensions and hydrogen concentrations.

Fig. 8. Neutron radiograph of a test fuel pin. The bright pellet has a higher enrichment than the other pellets for which reason centermelting occurred in this pellet and the neighbouring pellet. Cladding areas with a high hydrogen content are seen as bright spots.

Neutron Radiography, Development

Neutron radiographs of irradiated fuel pins can be used to measure the diameter of the pellets and the gap between pellets and cladding. To attain more accurate measurements, an extensive calibration programme was carried out; it included the fabrication of special fuel pins with varying pellet diameters and pellet-clad gaps. Radiographs of these pins were then made using different neutron sources and film types. The radiographs were evaluated by means of microdensitometers, projection microscope, and video-recorder.

Microgamma-Scanning

A lead-shielded apparatus was constructed for the investigation of the microdistribution of γ-active fission products in irradiated fuel pins. The apparatus will be interfaced with the mini-computer for direct evaluation of results.

Profilometry

A prototype of a new spring-type measuring head for use in fuel pin profilometry was constructed. The test results of diameter measurements showed that the standard deviation is close to 1 μm. The measuring head is now mounted on the profilometer installed in the hot cells and connected to a digitizer for the purpose of computerized data analysis.

PARTICIPATION IN INTERNATIONAL COLLABORATION

The Department is engaged in the following types of international collaboration: joint technical projects, committee work, reception of research fellows, and technical and scientific meetings. Participation in the OECD reactor project at Halden was continued. Six Danish fuel elements are at the moment being tested under irradiation in the Halden reactor.

A joint technical project, irradiation in the DR 3 of zircaloy-clad uranium-dioxide/plutonium-dioxide fuel rods, was continued (with the AB Atomenergi, Sweden). Also the programme on dispersion-strengthened zirconium alloys (with the UKAEA) was continued. Together with Atomic Energy of Canada Ltd. experiments are being carried out to investigate the in-pile creep properties of these alloys. Work continued on the joint programme on examination of advanced zirconium alloys for water reactors (with the UKAEA, United Kingdom, AB Atomenergi, Sweden, IFA, Norway and the Finnish AEC). The Department took part in a Scandinavian working group on hot cell techniques.

The Department was represented on the following committees:

The Halden Programme Group
The IAEA Working Group on "Reliability of Reactor Pressure Components"
The "Interramp" Project Committe
The CEC-NEA Working Group "Material and Mechanical Problems Related to the Safety Aspects of Steel Components in Nuclear Plants"
The Working Group "Nuclear Corrosion" under "The European Federation of Corrosion"
The EEC Advisory Committees for Programme Management: "Plutonium and Transuranium Elements", "Solid State Physics", and "Plutonium Recycling in Thermal Reactors"
The Council of the International Confederation of Thermal Analysis
The Nordic Committee for Thermal Analysis

and in the following Technical Commissions of the International Institute of Welding:

Commission I "Gas Welding and Allied Processes", Subcommission A "Brazing and Surfacing"
Commission IX "Behaviour of Metals Subjected to Welding"
Commission X "Residual Stresses and Stress Relieving. Brittle Fracture"

EDUCATION AND TRAINING

N. Hansen and K. Rørbo gave regular lectures on materials science to students at the Danish Academy of Engineering. N. Hansen, T. Leffers, and H. Lilholt acted as external examiners at examinations for the Technical University of Denmark.

Five scholarship holders, three from Egypt and two from Brazil, worked in the Department on projects in physical metallurgy and in radiography.

Undergraduate Projects

Nine students from the Department of Mechanical Engineering at the Danish Academy of Engineering worked in the Department on the following projects in preparation for their bachelors' theses:

E. Baastrup Jacobsen and V. Holstein:	Testing and Joining of Graphite Reinforced Epoxy
J. V. Rasmussen:	Mechanical Properties of Zr-Cr-Fe Alloys
J. J. Petersen:	Recrystallisation of Cu-Al and Cu-Al_2O_3 Alloys
P. R. Ipsen:	Flow Stress as a Function of Grain Size for 99.999% Cu
G. F. Madsen:	Construction of a Source of Acoustic Emission Using Material Susceptible to Stress Corrosion Cracking
F. Rønholdt Hansen:	Wear and Tear of Materials in a Nuclear Reactor
C. Riis Frederiksen:	Workability by Machining and Dimensional Changes by Presintering of Tool Bits
S. F. Henriksen:	Resintering of UO_2-Pellets

Post-graduate Projects

Four post-graduate students from the Technical University of Denmark worked in the Department on the following projects in preparation for their licentiate (Ph. D.) theses:

C. P. Debel:	Fracture Mechanics

P. Brøndsted Andersen:	Strengthening Mechanisms in Cu-Al-loys
B. S. Andersen:	Simulation Models for Deformation Processes, Especially Deep Drawing
I. Misfeldt:	Probabilistic Fracture Mechanics Applied to Fuel Rods

Degrees Conferred

The Technical University of Denmark conferred the degree of dr. techn. on T. Leffers and the degree of lic. techn. (Ph. D.) on V. Andreasen and O. Bøcker Pedersen.

PUBLICATIONS

Metallurgy Department Progress Report for the period 1 January to 31 December 1974.

Risø Report No. 327 (1975) 56 pp.

A description is given of the activities of the Metallurgy Department at Risø during 1974. The main fields of work are: General Materials Research, Materials Development, Fuel Elements and Fuel Modelling, and Materials Technology. Two articles, one on "Danish Developments in Computer Modelling and Overpower Testing of UO_2-Zr Fuel Pins", the other on "A New Model for the Plastic Deformation of Polycrystals", are also included in the report. A survey is given of the department's participation in international collaboration and of its activities within education and training. A list (with abstracts) of publications and lectures by the staff of the department during 1974 is included.

Additive styrkebidrag. (Additive Strength Contributions).

V. Andreasen, Risø-M-1714 (1975). Thesis. 128 pp.

A literary review of theories and models proposed for dispersion hardening, solid solution hardening, grain boundary hardening, work-hardening of dispersion hardening alloys and for addition of strength contributions is given.

The movement of a dislocation line through an array of different kinds of obstacles was examined in order to investigate the interactions between different hardening mechanisms.

Experimentally the plastic deformation at room temperature of Cu, CuAg, Cu-Al_2O_3, and CuAg-Al_2O_3 alloys was examined as a function of composition and volume fraction. The alloys were in the form of polycrystals and single crystals, and the single crystals were deformed in the $[112]$-direction.

The solid solution hardening is shown to be directly additive to the other strengthening mechanisms.

The strength contribution from grain boundaries is suggested to be dependent on the contribution from other strengthening mechanisms and the corrected strength contribution from the grain boundaries is shown to be additive to the other contributions.

Maximum Fiber Stress in Bending Creep.

J. B. Bilde-Sørensen, J. Amer. Ceram. Soc. 58 (1975) 70.

The equation relating the bending moment, M, and the maximum fibre stress, σ_{max}, in a bending creep test has hitherto been derived under the assumption of a power law relationship between stresses and strain rates. In this note it is shown that bending moments can be transformed to maximum fibre stresses without any prior assumption about the creep law, since the only necessary knowledge is the value of $d \log \dot{\varepsilon} / d \log M$ which can be determined experimentally. The equation is of particular usefulness when the stress sensitivity changes through the bending beam.

Prediction of the Creep Properties of Discontinuous Fibre Composites from the Matrix Creep Law.

J. B. Bilde-Sørensen, O. Bøcker Pedersen, and H. Lilholt, Risø-M-1810 (1975) 19 pp.

Existing theories for predicting the creep properties of discontinuous fibre composites with non-creeping fibres from matrix creep properties, originally based on a power law, are extended to include an exponential law, and in principle a general matrix law. An analysis shows that the composite creep curve can be obtained by a simple displacement of the matrix creep curve in a log σ vs. log $\dot{\varepsilon}$ diagram. This principle, that each point on the matrix curve has a corresponding point on the composite curve, is given a physical interpretation. The direction of displacement is such that the transition from a power law to an exponential law occurs at a lower strain rate for the composite than for the unreinforced matrix. This emphasizes the importance of the exponential creep range in the creep of fibre composites. The combined use of matrix and composite data may allow the creep phenomenon to be studied over a larger range of strain rates than would otherwise be possible. A method for constructing generalized composite creep diagrams is suggested. Creep properties predicted from matrix data by the present analysis are compared with experimental data from the literature.

Risø har fået nyt elektronmikroskop. (The New Electron Microscope at Risø).

J. B. Bilde-Sørensen and J. Lindbo, ingeniøren 1 No. 1 (1975) 41.

A description of the department's new JEOL-100C electron microscope with scanning attachment is given. Some of the experimental techniques are shortly presented.

Kontinuerlig diametermåling med stor nøjagtighed. (Continuous Diameter Measurement with Close Accuracy).

C. Bjerring and J. Domanus, Dansk Tekn. Tidsskr. 99 No. 5 (1975) 10-13.

For continuous diameter measurements of nuclear fuel rods a special spring-type measuring head was developed. Problems related to such measurements are discussed and measuring principles are given. With this type of measuring head accuracy of 1 μm in diameter measurement and a translation accuracy of 25 μm is possible. Factors influencing accuracy and other application possibilities are discussed.

A Unified Theory of Melting, Crystallization and Glass Formation.

R. M. J. Cotterill, E. J. Jensen, W. Damgaard Kristensen, R. Paetsch, and P. O. Esbjørn, Journal de Physique Colloque 36 (1975) C2-35-48.

The abstract appeared in the previous progress report.

Forskningsorganisation og medarbejderindflydelse. (Research Organization and Staff Influence).

N. Hansen, Management 10 (1975) 254-256.

The organization of the Metallurgy Department at Risø is discussed with special emphasis on the flexibility (with regard to both research and personnel) and on the influence of the employees.

Recristallisation accélérée et retardée dans les produits renforcés par des dispersions.

N. Hansen, Mem. Sci. Rev. Met. 72 (1975) 189-203

The effect of dispersed particles in a metal on the recrystallization behaviour has been studied on a review basis supplemented with new experimental results. Retarded and accelerated recrystallization is dealt with and the effect of particle parameters as spacing, size, shape and distribution is discussed.

Plutonium kan bruges til uranberigning. (Plutonium can be used for Uranium Enrichment).

H. Hougaard, ingeniøren 1 No. 17 (1975) 10-12.

Advantages and disadvantages by using plutonium enrichment instead of uranium enrichment in light water power reactor fuel pins are discussed. The post-irradiation examinations on plutonium enriched fuel pins, which are carried out on contract basis at Risø, are described in detail together with results from the examinations.

Brændselselementerne - atomreaktorens livsnerve. (The Fuel Elements - the Life Nerve of the Nuclear Reactor).

A. Jensen, Erhvervsbladet 12 No. 9 (1975) 26-27.

The article gives a brief description of the nuclear fuel cycle with special emphasis on uranium reserves and the fabrication of fuel elements. Some key measures of the fuel economy are included.

Mathematical Description of WAFER-1, a Three-Dimensional Code for LWR Fuel Performance Analysis.

N. Kjær-Pedersen, Nucl. Eng. and Design. 35(1975) 387-398.

This article describes in detail the mathematical formulation used in the WAFER-1 code, which is presently used for three-dimensional analysis of LWR fuel pin performance. The code aims at a prediction of the local stress/strain history in the cladding, especially with regard to the ridging phenomenon. In order to achieve this, a clad model based on shell theory has been developed. This model interacts with a detailed finite difference pellet model which treats radial and transversal cracking in the pellet in a deterministic way, based on certain assumptions with respect to the cracking pattern. Pellet and clad creep are taken into account. The inner core of the pellet, bounded by a specified isotherm, may be treated as a viscous material. Axial force exchange between pellet and clad is also included. The axial loading is distributed on the pellet end face with due regard to any pellet dishing. An arbitrary power history may be used as input to the model.

Performance Analysis of PWR Power Ramp Tests.

P. Knudsen and N. Kjær-Pedersen, ASME pamphlet No. 75-WA/HT-68 (1975) 8 pp.

Three identical UO_2-Zr PWR test fuel pins were irradiated to a burnup of 12,900 MWD/t UO_2 in pressurized water at 15 MN/m^2, at heat loads decreasing from about 500 W/cm to 340 W/cm. Subsequent power increases to approximately 540 W/cm, at a rate of 20 W/cm-min, produced cladding failure in at least two of the fuel pins. The hot-cell examinations revealed several very small cladding cracks, indicating that the failures were marginal. The cases were analyzed by means of the three-dimensional computer model WAFER-1, developed for LWR fuel performance analysis. The computer calculations showed that the local fuel-clad interaction in these experiments would in fact result in cladding failure. This paper explains in detail the modelling of the fuel pin behavior in the above cases and presents selected hot-cell results. Finally, the validity of the model concepts as applied to commercial PWR fuel, is assessed.

Overpower Performance of a PWR Test Fuel Pin.

P. Knudsen, K. Hansen, and B.S. Johansen, Atomwirtschaft-Atomtechnik 20 (1975) 514-515.

A PWR type fuel pin was irradiated to 12,900 MWD/t UO_2 at heat loads decreasing to 340 W/cm. A subsequent power increase to 540 W/cm produced cladding failure, apparently similar to previously reported BWR failures.

Dislocation Loops with a ⟨100⟩ Burgers vector Produced by 1 MeV Electron Irradiation in FCC Copper-Nickel.

T. Leffers and P. Barlow, Phil. Mag. 32 (1975) 491-496.

Dislocation loops with Burgers vector a⟨100⟩ are formed in Cu-Ni alloys during 1 MeV electron irradiation in a high-voltage electron microscope at 350°-400°C. The dislocation loops are of interstitial type and pure edge in character with ⟨110⟩ line vectors. Some of the loops are seen to dissociate into loops with Burgers vector a/2⟨110⟩.

A Kinematical Model for the Plastic Deformation of Face-Centred Cubic Polycrystals.

T. Leffers, Risø Report No. 302 (1975). Dissertation. 114 pp.

A kinematical model for the plastic deformation of f.c.c. polycrystals is proposed - with the emphasis on the way in which material continuity is maintained. The model deviates from the Taylor theory, the deviations being ascribed to the inhomogeneous deformation originating at the dislocation pile-ups at the grain boundaries. For materials with high stacking-fault energy dislocation pile-ups (and hence inhomogeneous deformation) are suggested to form at the boundaries where the approaching dislocations are predominantly edge dislocations. For materials with low stacking-fault energy pile-ups are suggested to form at all boundaries. The model is based on the similarity between calculated and experimental textures and on metallographic observations.

On the Misfit between the Grains in a Deformed Sachs Polycrystal and its Relation to the Inhomogeneous Deformation of Real Polycrystals.

T. Leffers, Scripta Met. 9 (1975) 261-264.

The misfit in a polycrystal deformed according to Sachs (with single glide in the individual grains) is calculated as a function of strain. The variation of misfit with strain is approximately linear, which agrees with Ashby's suggestion for the strain dependence of the density of "geometrically necessary dislocations". On the basis of the calculated misfit one can obtain an estimate of the intragranular orientation differences; this theoretical estimate is in good agreement with the orientation differences observed experimentally.

Twinning and Texture.

T. Leffers and P. Kayworth, In: 3e Colloque Européen sur les Textures de Déformation et de Recristallisation des Métaux et leurs Applications Industrielles, Pont-a-Mousson, France, 19-21 June 1973. 149-171.

The abstract appeared in the progress report for the period 1 Januar to 31 December 1973.

Discussion on "On the Bauschinger Effect in Unidirectionally Solidified Eutectic Al-Al_3Ni Crystals" by Lasalmonie and Martin.

D. R. Clarke and H. Lilholt, Scripta Met. 9 (1975) 93-98.

The data on the Al-Al_3Ni crystals are analysed in terms of recent models for internal stresses in fibre reinforced composites.

Elektronisk Data Behandling af Trækprøveresultater. (Computer Processing of Tensile Test Results).

B. Weiler Madsen, ingeniøren 1 No. 8 (1975) 8-10.

The use of electronic data processing of tensile test results are discussed with special reference to the INSTRON-5 program developed at the Metallurgy Department at Risø.

Irradiation Embrittlement of Pressure Vessel Steels. IAEA Research Agreement No. 1071/CF.

A. Nielsen and J. Westermahn, In: Report No. IAEA-176, Research Coordination Meeting on Irradiation Embrittlement of Reactor Pressure Vessel Steels Organised by the International Atomic Energy Agency, Held in Vienna 23-25 October 1974. (IAEA, Vienna, 1975) 219-242.

A Standard Research Programme was approved by the Coordinating Meeting on the 12th of May 1971 of the Working Group covering Engineering Aspects of Irradiation Embrittlement of Pressure Vessel Steels. This Working Group was set up by the International Atomic Energy Agency.

Several institutes in different countries agreed on doing irradiation experiments according to the approved programme on steel A 533B from the American HSST programme.

The Danish contribution covering tensile, impact, and hardness testing of non-irradiated steel and steel irradiated at 290°C to 2×10^{19} n_f/cm^2 is presented in this report.

Spændende opgave for danske svejsere. (An Interesting Task for Danish Welders).

J. Olsson and P. Dreves Nielsen, Metal 61 [11], (1975), 22-23 and Svejsning 2 [6], (1975), 126-127.

The fabrication of fuel elements is described, e.g. choice of materials, welding procedure, and control of welds. Also perspectives for fuel element production are discussed.

Steady-State Creep of Discontinuous Fibre Composites.

O. Bøcker Pedersen, Risø Report No. 329 (1975). Thesis. 74 pp.

A review is given of the relevant literature on creep of composites, including a presentation of existing models for the steady-state creep of composites containing aligned discontinuous fibres where creep of the matrix and fibres is assumed to follow a power law. A model is suggested for predicting the composite creep law from a matrix creep law given in a general form, in the case where the fibres do not creep. The composite creep law predicted by this model is compared with those predicted by previous models, when these are extended to comprise a general matrix creep law. Experimentally, pure copper and composites consisting of aligned discontinuous tungsten fibres in a copper matrix were creep tested at a temperature of 500°C. The results indicate a relatively low stress sensitivity of the steady-state creep-rate for pure copper and a relatively high stress sensitivity for the composites. This may be explained by the creep models based upon a general matrix creep law. A quantitative prediction shows promising agreement with the present experimental results.

Incompatibility Between Zircaloy-2 and Inconel X-750 During Temperature Transients.

M. R. Warren, K. Rørbo, and E. Adolph, J. Nucl. Mat. 58 (1975) 185-188.

The incompatibility of Zircaloy-2 and Inconel X-750 has been investigated between 1000°C and 1200°C (1200°C being the currently allowable maximum temperature in the acceptance criterium for ECCS for water reactors). It has been found for the temperatures of 1000°C and 1200°C that oxide thicknesses of 2 and 30 μm respectively protect the Zircaloy-2 against attack by Inconel X-750.

The Influence of Vacancy Flux Supersaturation and Gas Concentration on Void Nucleation.

B. N. Singh and A. J. E. Foreman, In: Consultant Symposium. The Physics of Irradiation Produced Voids, Harwell, England, 9-11 September 1974. Edited by R. S. Nelson (U. K. A. E. A., Harwell, 1975) AERE-R-7934. 205-211.

The abstract appeared in the previous progress report.

Summary of a Theory for Void Nucleation during Irradiation in Terms of Brownian Motion of Vacancy-Gas Atoms.

B. N. Singh and A. J. E. Foreman, Scripta Met. 9 (1975) 1135-1139.

A new theory for void nucleation during irradiation has been developed in terms of Brownian motion of vacancy-gas atom complexes. The theory has been formulated to predict the scale of nucleation which can be directly compared with experimental observations. The effects of damage rate, dislocation density, surface energy, and gas concentration on the scale of void nucleation have been calculated for an austenitic stainless steel under irradiation at 600°C. The predicted effect of gas concentration on the scale of void nucleation has been compared with experimental results and found to be in a good agreement. The present note presents a summary of the detailed theoretical and experimental investigations.

Swelling Resistance Induced by Grain Refinement and Particle Dispersion in Austenitic Stainless Steel during High Energy Electron Irradiation.

B. N. Singh, In: Properties of Reactor Structural Alloys after Neutron or Particle Irradiation. ASTM Special Technical Publications 570 (ASTM, Philadelphia, U. S. A., 1975) 543-554.

The abstract appeared in the previous progress report.

LECTURES AND CONFERENCE CONTRIBUTIONS

Weak-Beam Electron Microscopy of Dislocations in Sapphire

J.B. Bilde-Sørensen, A.R. Thölen, D.J. Gooch, and G.W. Groves, presented at the 4th Nordic High Temperature Symposium, Helsinki, June 1975. (Proceedings to be published).

Experimental evidence of the existence of $\langle 01\bar{1}0 \rangle$ dislocations in the $\{11\bar{2}0\}$ prism plane in sapphire has been obtained by transmission electron microscopy. By the weak-beam technique it has been shown that the $\langle 01\bar{1}0 \rangle$ dislocation may dissociate into 3 partials. The partials all have a Burgers vector of $\frac{1}{3}\langle 01\bar{1}0 \rangle$ and are separated by two identical faults. The distance between two partials is in the range 95-135 Å (depending on the edge-screw character), corresponding to a fault energy of around 300 erg/cm^2. Perfect $\langle 01\bar{1}0 \rangle$ dislocations have also been observed. These dislocations exhibited either one or two peaks when imaged in the (03$\bar{3}$0) reflection by the weak-beam technique. The interpretation of the electron micrographs has been supported by computer simulation of the dislocation images.

High Temperature Tensile and Creep Properties of Tungsten Fibre Reinforced Nickel Composites.

H. Carlsen and H. Lilholt, presented at the 4th Nordic High Temperature Symposium, Helsinki, June 1975. (Proceedings to be published).

Specimens consisting of continuous tungsten fibres in a nickel matrix were made by liquid infiltration and by powder-forging. Tensile testing showed that the cast composites were rather brittle below 300-400°C, and had low and scattered tensile strengths compared to powder-forged composites. Above this temperature range the two types of composites behaved similarly. Creep properties of cast specimens were investigated at 800 and 900°C. The results showed the expected dependence of creep rate on tensile stress, but the absolute creep strengths were low compared to a simple model of a composite with creeping, continuous fibres.

Production of Tungsten Fibre Reinforced Nickel Composites by Liquid Infiltration.

H. Carlsen and H. Lilholt, presented at the 4th Nordic High Temperature Symposium, Helsinki, June 1975. (Proceedings to be published).

Production of fibre-reinforced metals by liquid infiltration was studied using continuous 500 μm tungsten fibres and pure nickel as matrix. By high frequency induction heating the mould was heated in a purified argon atmosphere, the coil being designed so that the fibres were preheated to a temperature lower than the melting point of the nickel. Specimens of 3 mm in diameter and up to 150 mm in length were produced by this method. The resulting polycrystalline nickel contained up to 50 v/o fibres that had recrystallized to some extent in the surface zone. The advantages of the method are easy and flexible handling and short duration of the casting operation, the disadvantages in relation to these materials being dissolution and recrystallization of the fibres.

Getter Brazing Below 1025°C of Untreated Reactive Metals Containing High-Temperature Nickel Alloys.

J. Christensen and K. Rørbo, presented at the Second International Brazing and Soldering Conference, London, October 1975.

Manuscript has been published in Weld. J. 53 (1974) 460s-464s. For abstract see previous progress report.

The Interplay between Physical Metallurgy and Engineering in the Nuclear Field.

N. Hansen, presented at the Rosenhain Centenary Conference, London, September 1975. (Proceedings to be published).

Discussion of specific problems e.g. fuel element development requiring a tight collaboration between experts in different fields as mathematical modelling, physical metallurgy and engineering.

Effect of Released Fission Gases on UO_2-Temperatures.

G. Fayl, K. Hansen, and B.S. Johansen, presented at the Enlarged Halden Program Group Meeting, Geilo, March 1975. (Transcript available, 14 pp.).

Fuel temperature measurements carried out in well instrumented irradiation rigs indicated that 15% fission gases in the stainless steel capsule with helium filling gas had no measurable influence on the temperatures of the UO_2 pellets. Furthermore, 40% fission gases in the capsule resulted in a temperature increase of a maximum 70°C. In both cases, currently used thermal models predict temperature increases of 20-30°C and 110-140°C, respectively.

It is concluded that underestimated effects of radial relocation and solid- to solid heat transfer are likely to be responsible for the discrepancy.

Experience with the Three-Dimensional Fuel Performance Model WAFER.

N. Kjær-Pedersen, presented at the 3rd International Conference on Structural Mechanics in Reactor Technology, London, September 1975. (Transcript available, 10 pp.).

Since the completion of the first version of WAFER, the Danish 3-D performance model for pelletized fuel, during the summer of 1974, an extensive program has been carried out with the purpose of verifying the model by comparing model predictions with results from the Danish fuel irradiation program.

The model aims at a prediction of local stresses and strains in the cladding, especially around the ridges. This paper presents the model concepts in detail and assesses their validity by comparison of computer runs with reactor experiments.

Testing of the Danish Fuel Performance Model WAFER-1.

N. Kjær-Pedersen, presented at the Enlarged Halden Program Group Meeting, Geilo, March 1975. (Not available).

The Danish three-dimensional computer model WAFER-1 for analysis of pelletized water-reactor fuel performance has been applied to a typical PWR test fuel irradiation case. This paper first gives a brief survey of the code architecture along with an assessment of its numerical performance. Then the application of the code to the fuel irradiation case is explained and the results discussed. The paper concludes that the stresses, strains and center temperatures calculated by the code are in agreement with general experimental evidence. It is further concluded that the code accounts very well for the shape of the permanent ridges. The ridge-heights are very sensitive to the choice of clad creep-data.

Performance Analysis of PWR Power Ramp Tests.

P. Knudsen and N. Kjær-Pedersen, presented at the ASME Winter Annual Meeting, Houston, Texas, December 1975. (Manuscript published as ASME pamphlet).

Power Ramp Test with a PWR Fuel Pin.

P. Knudsen, K. Hansen, and B.S. Johansen, presented at the Enlarged Halden Program Group Meeting, Geilo, March 1975. (Transcript available, 12 pp.).

A UO_2-Zr PWR test fuel pin was irradiated to a burnup of 12,900 MWD/t UO_2 in water pressurized to 150 at, at heat loads decreasing from about 500 W/cm to 340 W/cm. A power increase to 540 W/cm at a rate of 20 W/cm·min. produced cladding failure. The first hot-cell observations indicate that the failure has the same appearance as reported for BWR overpower tests.

Cladding Failure in BWR and PWR Overpower Tests.

P. Knudsen, presented at the ANS-CNA Meeting "Commercial Nuclear Fuel Technology Today", Toronto, April 1975. (Not available).

UO_2-Zr test fuel pins were irradiated at decreasing heat loads and characterized non-destructively. The power levels were then increased at controlled power ramp rates and the new full power was maintained until failure indication. Clad thickness and pellet-clad gap were approx. 0.6 mm and 0.2 mm. Additional details were as follows:

Test type	OD mm	Burnup MWD/t UO_2	Latest power W/cm	Overpower level, W/cm	Ramprate W/cm. min.
BWR	14.0	21,000	350	420	30
PWR	10.7	13,000	340	540	20

The hot cell examinations revealed numerous, tiny cladding cracks, both at and away from the pellet interfaces. The crack appearance is the one to be expected from a combination of a "mild" fuel-clad mechanical interaction and a stress-corrosion type mechanism. The smallness of the cracks indicate that the overpower levels were just above those required for cladding failure. At the present stage of examination there is no difference in the failure appearance for the two types of test fuel pin.

Irradiation Induced Dislocation Climb Sources.

T. Leffers and P. Barlow, presented at the Fourth International Conference of High Voltage Electron Microscopy, Toulouse, September 1975. (Proceedings to be published).

Dislocation climb sources have been observed in Cu-Ni alloys irradiated at 350-450°C with 1 MeV electrons in a HVEM.

The dislocations are emitted in the form of interstitial loops. The following types of loops have been observed: single- and double-faulted Frank loops, prismatic loops with $a/2\langle 110\rangle$ type Burgers vector, and pure edge dislocation loops with a $\langle 100\rangle$ type Burgers vector.

The black-dot contrast, which appears at the loop sources, may vary during the growth of a loop such that the black dot may grow into a loop of sufficient size, before the contrast reappears at the source.

Composites in Scandinavia.

H. Lilholt, presented at the 1975 International Conference on Composite Materials, Boston, April 1975. (Not available).

A brief summary of activities within the field of composite materials, their use and fabrication, in Scandinavia.

Session IV: Mechanical and Physical Properties. Rapporteur's Report.

H. Lilholt, presented at the 1975 International Conference on Composite Materials, Geneve and Boston, April 1975. (Proceedings to be published).

A critical discussion of five papers on composite materials is presented. Structural and mechanical properties are discussed.

A Study of Nickel Reinforced with Tungsten Wires, a Potential High Temperature Material.

H. Lilholt and H. Carlsen, presented at the 1975 International Conference on Composite Materials, Geneve and Boston, April 1975. (Proceedings to be published).

Fabrication by liquid infiltration has been investigated. It is possible to produce specimens of 3 mm diameter and 10-15 cm length with continuous tungsten fibres in a nickel matrix; the fibre diameter is 0.5 mm and the volume percent is up to 50. The quality of the composites is acceptable. The mechanical properties in tension have been found to agree with the law of mixtures; the strength is unusually low at temperatures below 300-400°C, but acceptable at temperatures up to about 1000°C. The creep strength at 800 and 900°C is in reasonable agreement with expected values based on composites with creeping fibres.

Metal Matrix Composites.

H. Lilholt, presented at the 4th Nordic High Temperature Symposium, Helsinki, June 1975. (Proceedings to be published).

The interest in metal matrices for fibre reinforced composites will be indicated, in particular for applications at high temperatures. Recent progress in the understanding of the creep behaviour of composites with parallel fibres will be presented. Possible dislocation processes at fibres will be treated on a geometrical basis.

Atomkraft! Ja/Nej? (Nuclear Power, Yes or No?).

B. Weiler Madsen, presented to the associations "Natur og Ungdom" and "Socialistisk Folkeparti", Ringsted, October 1975. (Not available).

Political and economical questions in connection with Denmark's future energy supply were discussed.

Special Problems in the COD-Technique.

A. Nielsen, presented at the COD Symposium, Helsinki, February 1975. (Transcript available, 2 pp.).

During COD testing the critical point is basically the point of crack extension. On load-COD diagrams generally recorded during the testing it is often easy to see when crack extension takes place, but slow crack growth might not be recognized from the diagram. A few auxiliary methods of detecting slow crack growth will be mentioned.

In steel structures the slow crack growth might not be critical, but it is often justified to consider the maximum load as the critical point. For tough steels the maximum load is not defining δ_c accurately, but this is of minor importance when δ_c is large and critical crack lengths in the structure are considerably larger than the plate thickness of the steel.

A feature related to testing of steel pieces with crack-like defects is that the transition, ductile to brittle fracture, is taking place within a very small temperature range and with a very large difference in δ_c. With respect to the failure probability of a steel structure it might be significant to consider the difference between the transition temperature of the steel and the operation temperature of the structure and not only add a safety factor in the calculation of the critical crack length.

Instrumented Impact Testing as a Way to Obtain Further Information on the Behaviour of Steel in Welded Constructions.

A. Nielsen, presented at the COD Symposium, Helsinki, February 1975. (Transcript available, 18 pp.).

Based on the experience gained by instrumented impact testing of ten different mild steels using test pieces of different geometrical shape (Charpy V-notch, Charpy knife-notch, DVM, Schnadt K_0, $K_{0.5}$, K_1 and K_2), some general features are seen of the fracture process during impact testing.

Steels can be divided into two main groups which are significantly different with respect to the behaviour during Charpy V-notch testing. The difference vanishes when a crack-like notch is used, and other properties of steel are revealed.

It is evident that even when modified, the impact testing bears little resemblance to what is happening in an actual steel construction. For the purpose of investigating the fracture conditions in welds, it seems more significant to relate the dynamic aspects to the speed of propagation of the crack when it starts to penetrate the volume considered at a certain stress level.

The Use of Acoustic Emission for Detection of Defects as They arise during Fabrication.

A. Nielsen, presented at the Annual Meeting 1975 of the International Institute of Welding, Tel Aviv, July 1975. Transcript available, 19 pp.).

Three different applications of acoustic emission (AE) technique are considered:

1. Surveillance during welding to detect defects as they are formed. The welding processes considered are arc welding, electro slag welding, electron beam welding, resistance spot welding and a few other welding methods.
2. Surveillance immediately after welding to detect delayed cracking.
3. Surveillance during stress relief to detect reheat cracking.

Work done within this field indicates that the technical difficulties in the application of AE technique can be handled, and that advantages could be gained with respect to production rate and quality.

Steady-state Creep of Copper-Tungsten Fibre Composites.

O. Bøcker Pedersen, presented at the 1975 International Conference on Composite Materials, Geneve and Boston, April 1975. (Proceedings to be published).

Pure copper and composites consisting of aligned discontinuous tungsten fibres in a copper matrix have been creep-tested at a temperature of 500°C. The results indicate a relatively low stress sensitivity of the steady-state creep-rate for the pure copper and a relatively high stress sensitivity for the composites. This is explained on the basis of an analysis of existing creep models. A quantitative prediction of this analysis shows promising agreement with the experimental results.

A New Theory for Void Nucleation.

B.N. Singh and A.J.E. Foreman, presented at the Annual Meeting 1975 of Selskabet for Faste Stoffers Fysik og Kemi, Rungsted, May 1975. (Not available).

Apart from the intrinsic academic interest in the nucleation process itself, the study of void nucleation has an immediate and direct relevance to fast breeder reactor technology. Since in the existing theoretical treatments the effects of some rather important physical aspects pertinent to the nucleation process are not included, we have attempted to develop a new and conceptually simple theory which takes account of all the essential physical aspects of the nucleation process during irradiation and the predictions of which are readily accessable to experimental verification. The theory is formulated in terms of Brownian motion of voids in embryonic and post-embryonic states. The nucleation model will be described in detail. The limitations and scope of the model will be discussed. The calculated scale of nucleation will be compared with experimental results.

High Temperature Studies of Thermodynamic Properties and Structures of Non-stoichiometric Cerium Dioxides.

O. Toft Sørensen, presented at the 4th Nordic High Temperature Symposium, Helsinki, June 1975. (Proceedings to be published).

Cerium dioxide, often used as a model material for plutonium oxides in research on fuel materials for nuclear power reactors, easily forms non-stoichiometric oxygen-deficient oxides with the composition CeO_{2-x}. In order to study the nature of this non-stoichiometry, which to a great extent determines the properties of these oxides, thermodynamic data were determined by thermogravimetric analysis in the temperature range 900-1400°C in atmospheres of known oxygen pressures. Under the conditions covered in these experiments, compositions within the range $2.00 \geq O/M \geq 1.75$ could be obtained. A detailed analysis of the thermodynamic data according to defect theories shows that the non-stoichiometric α'-phase region in the phase diagram, which exists at higher temperatures and which was previously described as a single, grossly non-stoichiometric phase, can be divided into subregions each having a characteristic defect structure. The finer details of the thermodynamic data also suggests that some of the subregions can be further split into ordered intermediate phases with compositions following the series M_nO_{2n-2}. In order to determine the structure of some of the intermediate phases formed, high temperature X-ray diffraction studies were also carried out. These measurements show that the defects can order at higher temperatures in monoclinic superstructures.

Thermodynamic Studies at Higher Temperatures of the Phase Relationships of Substoichiometric Plutonium and Uranium/Plutonium Oxides.

O. Toft Sørensen, presented at the 5th International Conference on Plutonium and other Actinides, Baden-Baden, September 1975. (Proceedings to be published).

Partial molar thermodynamic quantities for oxygen in non-stoichiometric Pu and U/Pu oxides were determined by thermogravimetric measurements in CO/CO_2 mixtures in the temperature range 900-1450°C. A detailed analysis of the thermodynamic data obtained, as well as data previously published for these oxides, shows that the substoichiometric phase range in the phase diagram, previously described as a grossly non-stoichiometric single phase, can be divided into several subregions each with a characteristic type of defect. The pattern of subregions found for the mixed oxides is not the same as that found for PuO_{2-x} because of the greater stability of the mixed oxides. High temperature X-ray diffractometry measurements which were performed on corresponding U/Ce oxides, also reveal this increased stability of mixed oxide systems.

Studies of Non-stoichiometric Oxides by Thermoanalytical Methods.

O. Toft Sørensen, presented at the 4th Scandinavian Symposium on Thermal Analysis, Stockholm, August 1975. (Not available).

Non-stoichiometric oxides can be divided into metal-deficient and oxygen-deficient oxides, and a few examples of each type are given in order to show the materials of interest in this field. After a short review of the methods used in the study of these oxides an account is given of the methods used in and the results obtained from a recent thermogravimetric investigation in atmospheres of controlled oxygen pressure on cerium oxides, plutonium oxides and mixed uranium/plutonium oxides, which are all of special interest in research on fuels for nuclear power reactors.

The $\Delta\bar{G}_{O_2}$ *versus* ln x plots obtained for the oxide systems examined clearly show that the non-stoichiometric phase range can be divided into several subregions, which each can be described by a characteristic n. Some of the subregions can still be considered as non-stoichiometric but for other regions the data indicates the existence of a succession of intermediate, ordered phases separated by two-phase regions. An interesting feature of these intermediate phases is that their composition can be described by the series M_nO_{2n-2}.

Studies of Non-Stoichiometric Ocides by Thermoanalytical Methods.

O. Toft Sørensen, **presented at Wissenschaftlichen Tagung und Mitgliederversammlung der Gesellschaft fΠr Thermische Analyse, Kassel, June 1975. (To be published in Thermochimica Acta).**

Non-stoichiometric oxides can be divided into metal-deficient and oxygen-deficient oxides, and a few examples of each type are given in order to show the materials of interest in this field. After a short review of the methods used in the study of these oxides, an account is given of the methods used in and the results obtained from a recent thermogravimetric investigation in atmospheres of controlled oxygen pressure on cerium oxides, plutonium oxides and mixed uranium/plutonium oxides, which are all of special interest in research on fuels for nuclear power reactors.

STAFF OF THE DEPARTMENT

(as at 31 December 1975)

N. Hansen, head of department

Scientific staff

Adolph, E.
Agerup, C.C.
Andersen, B.S. [3]
Andreasen, P. Brøndsted [3]
Bagger, C.
Bilde-Sørensen, J.B.
Borring, J. [1]
Carlsen, H.
Christensen, J.
Debel, C.P. [3]
Domanus, J. [1]
Fishler, M.
Gundtoft, H.E.
Higgy, H.R. [4]
Hougaard, H.
Jensen, A. [1]
Johansen, B.S.
Kjær-Pedersen, N. [1]
Knudsen, P.
Laursen, K.M.
Leffers, T.
Lilholt, H.
Lystrup, Aa. [5]
Nielsen, A.
Pedersen, O. Bøcker [6]
Rørbo, K.
Singh, B.N.
Strange, S.
Swindlehurst, W.E.
Sørensen, O. Toft
Vigeholm, B.

Technical staff

Andersen, J. [1]
Aukdal, J.A. [2]
Chabert, O.
Dreves, P.
Dysted-Nielsen, K.E.
Frederiksen, H.
Jensen, F.
Jensen, H.E.
Jensen, P.V.
Jespersen, J. [1]
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Olsen, N.H.
Olsen, O.
Olsen, [illegible]
Rasmussen, A.
Sandsted, K. [1]
Strauss, T.R.
Sørensen, E. [1]

Office staff

Eichen, A.M.
Nielsen, M.
Olesen, G.
Simonsen, M. Van Zundert

1) Employee of the Elsinore Shipyard, Ltd.

2) Attached to the OECD Halden Reactor Project

3) Post-graduate student from the Technical University of Denmark

4) Scholarship-holder on leave from the Metallurgy Department, Egyptian AEC

5) Attached to the Nuclear Division, ORNL, USA

6) Attached to the Department of Metallurgy and Materials Science, University of Cambridge, England.

Consultants to the Department

Non-destructive testing	N. Nielsen (Danish Welding Inst.)
Physical Metallurgy	R.M.J. Cotterill (Technical University of Denmark)

ISBN 87 550 0379 6