FUEL FABRICATION AND POST-IRRADIATION EXAMINATION

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SUMMARY

This paper provides an overview of the AEC's BEVA and ELPROD facilities for the fabrication of nuclear fuel. It also describes the sophisticated Hot Cell Complex, which is capable of accommodating pressurised water reactor fuel and various other irradiated samples. Some interesting problems and their solutions are discussed.

OPSOMMING

Hierdie referaat verskaf 'n oorsig van die AEK se BEVA- en ELPROD-aanlegte vir die vervaardiging van kernbrandstof en die gesofistikeerde Warmselkompleks, wat die vermoë het om drukwaterreaktor brandstof en 'n verskeidenheid bestraalde monsters te hanteer, word ook beskryf. Enkele tegniese probleme wat ondervind is, word tesame met oplossings bespreek.

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INTRODUCTION

Through the years the AEC and its predecessors the Atomic Energy Board and NUCOR were to a greater or lesser extent involved in research and development of fuel fabrication.

Because of the threat of sanctions it was decided to erect a fuel fabrication plant for the manufacture of Materials Testing Reactor (MTR) fuel exclusively for use in the AEC's research reactor, SAFARI, as a means to ensure that SAFARI could be kept operational.

The Physical Metallurgy Department possessed a high level of expertise concerning melting and casting technology, and the conventional uranium-aluminium alloy manufacturing route was chosen. Reduced uranium enrichment (45 % U-235) meant a higher uranium content in the uranium-aluminium alloy, but no information was available on powder metallurgical techniques developed and employed elsewhere. The conventional route was therefore considered safer, especially with regard to schedules.

The ELPROD plant was erected during the second half of the seventies, and the first fuel elements were provided to SAFARI on 27 March 1980. To date, 60 fuel elements have been produced and successfully irradiated.

During October 1977 the Government of the Republic of South Africa gave instructions for the AEC to prepare for a possible project encompassing the erection of a fuel fabrication plant to satisfy ESKOM's requirements for pressurised water reactor (PWR) fuel for the two KOEBERG units near Cape Town. These instructions were formally ratified on 22 February 1978.

During April 1979 a contract was signed with a company of industrial architects and erection of the buildings started in January 1980. Final civil work was completed during December 1985.

Official qualification runs on the various components and assemblies started late in 1987 and the first four fuel assemblies were delivered to KOEBERG on 14 September 1988. Series production of the first reload for KOEBERG started during April 1988.

The decision to erect a Hot Cell Complex on the AEC's Pelindaba site coincided with the Government's instruction to erect the fuel fabrication plant.

The design of the Hot Cell Complex was initiated early in 1978 and was only finally completed during 1987. Civil work started during the latter half of 1981 and was completed in 1986. Equipment installation and cold commissioning were completed during 1989.

FUEL FABRICATION

The BEVA plant is rather unique in that it covers all required processes for the fabrication of PWR fuel. This entails the following:

(i) Uranium pellet production line, comprising UO_2 powder production from UF_6 received from the enrichment plant, pelletising line and uranium waste recovery plant.

(ii) Zircaloy tube and bar production plant, comprising all processes from feed material (zirconium dioxide) through to final finishing, non-destructive testing and inspection of cladding tubes, guide thimbles, instrumentation tubes and Zircaloy-4 bar material required for the production of end plugs.

(iii) Component manufacture facilities, including Inconel grid strap production, grid assembly, top and bottom nozzle fabrication, and the manufacture of hold-down springs, screws and other small components.

(iv) Assembly lines for fuel pin assembly, guide thimble assembly, skeleton assembly and fuel assembly, with associated non-destructive testing and inspection.

A layout of the site is given in Figure 1.

Plant capacities

The BEVA facility for PWR fuel is currently under-utilized because of limited local demand. The design capacity is 100 tU/a but this can be increased to 200 tU/a by means of limited capital expenditure and the introduction of a three shift system.

The capacity of the ELPROD plant is 100 MTR fuel elements per annum.

Problems experienced

In this section attention is given only to some typical examples of problems experienced in establishing the BEVA fuel fabrication plant for PWR fuel.

Product design

At the start of the project, virtually no information was available on product specifications and design parameters. AEC engineers were given the task to develop in-house specifications from available ASTM specifications, generic information on PWR reactor plant and fuel, and information available in the literature.

Plant and process design and layout

Initially both major projects discussed in this paper, BEVA and the Hot Cell Complex, were assigned to a relatively small group of approximately 65 engineers, scientists and technicians. These people had very limited knowledge of or experience in process and plant design but possessed well developed engineering, scientific and technical skills particularly in the metallurgical, mechanical and chemical engineering fields. As prior experience was unavailable, all processes were designed from basic principles and based on limited information available in technical literature. The basic philosophy applied to the process design problem was ultra conservative, to ensure that any incorrect decisions would always be in the direction of greatest safety.

During the past few years and in particular during the past year of production, it has been proven that the approach taken was the correct one and that an optimal process had been chosen from the product quality point of view.

Zircaloy cladding tube production

One of the more important aspects of the cladding tube specification is the so called contractile strain ratio, which is determined by the metallurgical texture of hexagonally close packed Zircaloy-4. This texture is in turn determined by the tube reduction schedule and tooling schedules.

A small team responsible for the Zircaloy tube plant developed various techniques for predicting the resultant texture of Zircaloy-4 cladding tubes for various reduction schedules and tooling designs. The techniques included the development of computer models detailing the profile of tooling for all the steps in any particular chosen reduction schedule in sufficient detail to allow evaluation and analysis on a microscopic scale. These computer programmes were supported by an in-depth study of available literature on texture and texture development in Zircaloy materials.

The theoretical work was initially tested by practical analyses of texture changes and texture development in Zircaloy sheet material which was cold rolled on a laboratory rolling mill. Through knowledge of material flow characteristics, deductions could be made for tubular material based on the results of sheet rolling experiments.

At a later stage the results of these predictions were confirmed by actual experimental work using tubular material and tools designed and manufactured in-house followed by extensive analyses on a X-ray goniometer. In doing so it was possible to ensure that the specification for contractile strain ratio could be achieved very soon after production trials started.

UF_6 to UO_2 conversion

UO_2 powder characteristics are directly determined by the process which is chosen to convert the enriched UF_6 gas to UO_2 powder. One of the major challenges to the group responsible for the process and plant design for the conversion process was to choose amongst the available wet and dry processes. A final choice was made after due consideration of resultant powder characteristics as well as patent restrictions and it was decided to make use of a dry, gaseous phase reduction of UF_6 with steam and hydrogen.

During 1978, a feasibility study on a small conversion kiln was performed by engineers, scientists and technicians (5 in number). Construction of the pilot kiln, which was commissioned in March 1980, started in 1979. The first 46 kg of good UO_2 were produced in January 1982.

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Designing the main plant could not be delayed until results became available from the pilot plant, and detail design was initiated during 1978. The conversion kiln was ordered during May 1980, before the pilot plant yielded product for experimental purposes. The process installation for the conversion kiln was completed in September 1982. Because the process was thoroughly designed from first principles and the pilot plant was available to test the designs and make necessary modifications, albeit barely ahead of the conversion kiln, the conversion kiln and associated processes yielded a good product from day one.

Proof of conformance to specifications

One of the major concerns during the early stages of the project was to prove conformance to specifications and consistency of product quality. This problem was addressed in the following two manners:

(i) Quality Management Programme

One of the first priorities was to establish a comprehensive Quality Management Programme Plan. It was decided to conform to the basic requirements of ASME/ANSI NQA-1 and system procedures were developed for each of the 18 requirements. Although this was the responsibility of the Quality Assurance Department, all line personnel were involved in the development of the programme, thereby ensuring acceptance and a high level of indoctrination at a very early stage. Implementation of the Quality Management Programme was and still is checked on a regular basis by formal audits and surveillances performed by persons independent of normal production line authority.

(ii) Qualification Programme

As part of the Quality Management Programme, an extensive qualification programme was defined. The qualification programme was comprised of the following steps:

(a) Manufacturing Test Programme, whereby the limits of the operating ranges of the individual processes or facilities were investigated;

(b) Evaluation Programme, whereby the various facilities and steps within a process line were coupled and the resultant products were fully evaluated to check compliance with specifications; and

(c) Formal qualification of processes, personnel and products, whereby compliance of processes with specific requirements, compliance of operators and inspectors with defined training and ability criteria, and compliance of products inclusive of final fuel assemblies with extended specifications had to be proven.

The end result of the Qualification Programme was the manufacture of 4 demonstration assemblies, which were delivered to KOEBERG on 14 September 1988 and which have now successfully completed one reactor cycle.

Proof of performance

Exhaustive post-irradiation examination of fuel pins extracted from removable pin fuel assemblies will be carried out. The first four such fuel pins were transported from KOEBERG to the AEC's Hot Cell Complex and were received on 1 May 1990. They will be examined during 1990.

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The four demonstration assemblies were compared with standard fuel purchased by ESKOM from external sources and which had undergone similar irradiation cycles. These demonstration assemblies were extensively examined and measured in the fuel pool after the first irradiation cycle. Preliminary results indicate that there are no significant differences between BEVA fuel and the standard fuel.

These measurements, as well as post-irradiation examination of fuel pins, will be repeated after the second and third irradiation cycles.

Future developments

Production of zirconium

The AEC has for some years been involved in the development of a unique process for the production of zirconium from zirconium dioxide via an aluminothermic reaction. It is anticipated that the first tubes from locally produced zirconium will be available for irradiation in SAFARI to determine in-pile characteristics by October 1992. A number of removable pins will subsequently be irradiated in KOEBERG after which a full qualification programme will be performed prior to fuel being manufactured from locally produced zirconium for use in KOEBERG. The anticipated completion date for the first core reload manufactured from locally sourced zirconium is 1995.

Product adaptations

Various minor adaptations of the product are receiving attention. One of the major programmes that may be embarked on at a later stage is the development of all-Zircaloy fuel. This need was identified from indications by ESKOM that replacement of Inconel grids with Zircaloy-4 grids may be required in future.

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HOT CELL COMPLEX

The requirement for a metallurgical Hot Cell Complex for the post-irradiation examination (PIE) of structural reactor materials became apparent during the late sixties and early seventies. Because the AEC had other commitments, satisfaction of this need had to be delayed.

The requirements changed substantially from the earlier needs when the BEVA project triggered very extensive anticipated requirements for PWR fuel examinations. It was therefore decided to plan and erect a complex capable of performing all anticipated PIE on PWR fuel to prove the performance of a totally "new" fuel design and vendor.

Figure 2 shows the ground floor plan of the AEC Hot Cell Complex. The facility consists of 3 high density (alpha, beta, gamma) concrete cells and 23 lead steel cells. The concrete cells and certain lead steel cells provide alpha, beta, gamma containment and shielding and allow operations to be performed under inert atmosphere.

The reception and pool area provides for the reception and unloading of flasks up to 80 tons loaded with PWR fuel assemblies or fuel pins. The storage pool can hold 28 PWR fuel assemblies, and also provides wall space for highly-active waste contained inside canisters. The water temperature can be regulated to below 40°C whilst water conductivity and pH can be controlled to PWR pool water specifications.

Technical and Scientific capabilities

The AEC's Hot Cell Complex has been designed and equipped to perform physical, chemical and metallurgical examination of:

- Full length PWR fuel assemblies or pins at any stage of burn-up;
- Other reactor fuel;
- Irradiated structural materials (eg. the KOEBERG surveillance ferritic samples); and
- Irradiated materials and samples irradiated in rigs in a materials test reactor.

The more noteworthy characteristics and capabilities of the Hot Cell Complex are as follows:

- Dismantling of fuel assemblies and elements;
- Sipping station to identify leaking pins;
- Neutron radiography (using the neutron source at SAFARI);
- Metrology (length, diameter and bow measurements on PWR fuel pins in the vertical position);
- Eddy current measurements;
- Macro- and microgammametry;
- Fission gas extraction and analysis;
- Hardness testing;
- Biaxial creep and burst testing;
- Tensile testing (room temperature to 400°C);
- Impact testing (-196°C to 300°C);
- Gas analysis (C, N, O, H);
- Wet chemical analysis and burn-up determination;
- Density measurement;
- Metallography and ceramography;
- Optical microscopy with image analysis; and
- Scanning electron microscopy with EDAX.

A complete waste (liquid, solid) management system supports the technical and scientific capabilities.

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Most equipment is computerized for fast processing of data.

Status

The facility:

1. has been (cold) commissioned;
2. is under IAEA safeguards; and
3. is under control of an ASME/ANSI NQA-1 Quality Management Programme.

The first licensing phase for the facility as required by the Council for Nuclear Safety has been completed and accepted. Four PWR fuel pins were recently received from KOEBERG.

Problems encountered and solved

Sanctions closed overseas nuclear facilities to South Africans seeking scientific and engineering collaboration. This caused the AEC to rely on its own resources for the specifications and design of the facility. South African engineering firms were sub-contracted to construct the Hot Cell Complex.

With little or no nuclear expertise available amongst the sub-contractors, many technical meetings between the professional engineers and scientists of the AEC and engineers from the sub-contracted firms were held, where the philosophy and technical specifications of the facility were discussed.

Typical design problems encountered were:

(i) No experience of casting high-density concrete existed in the Pelindaba region. Early attempts by the contractors at casting high density concrete were unsuccessful and the assistance of the Council for Scientific and Industrial Research was sought. After thorough evaluation of available technical publications, a procedure was drafted. Application of this procedure by the contractor ensured acceptable quality.

(ii) To dismantle PWR fuel assemblies inside cell 1 and to prevent overheating of the PWR fuel pins (for a 15 kW decay heat the fuel pins inside the assembly can reach 500°C in air if no forced cooled air flow is available) the assembly is transported underwater into cell 1 and placed inside a canal with 90 % of the assembly under water. Water circulating through this canal prevents overheating while dismantling of the assembly takes place on the section above floor level.

(iii) Where in-cell equipment and components were not available, either standard off-the-shelf instruments or components were adapted or designed and built from scratch. Many examples of such modifications can be seen in the Hot Cell Complex.

(iv) The unloading and storage pool walls were clad with 3mm thick 304L stainless steel sheet.

Welding procedures were formally qualified before the actual lining was welded in place. Automatic TIG welding machines were used to ensure consistent quality. All welds were evaluated by means of both dye penetrant and ultrasonic testing.

The total pool sheet surface was divided into an (X, Y) grid and the inside surfaces of the welded joints were covered by a drainage system imbedded in the concrete behind the sheets. All welds were hydraulically tested by incrementally filling the pools, allowing a time delay of 24 hours between defined water levels. The pipe outlets behind the grids were checked hourly for water leakage. No leaks were observed.

Future Developments

As the cells have not yet been commissioned with irradiated material, the next few years will be devoted to gaining experience and building expertise in operating the Hot Cell Complex as well as examining PWR fuel and other samples. Fuel pins from the first four BEVA demonstration fuel assemblies and tube samples irradiated in SAFARI as part of the evaluation program for locally produced Zircaloy-4 will provide the bulk of the work load.

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FIGURE 1

SITE LAYOUT: BEVA FUEL FABRICATION PLANT

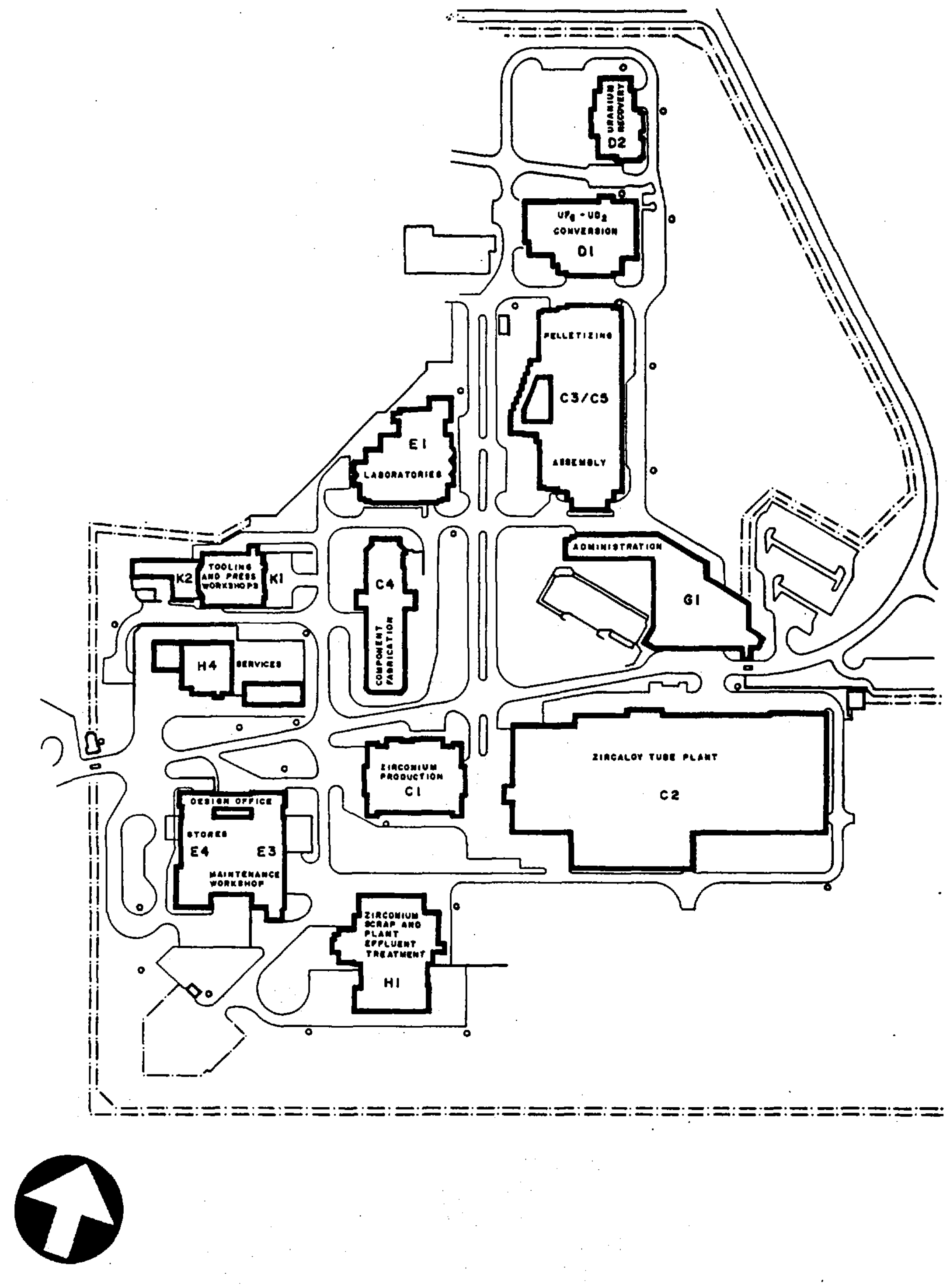
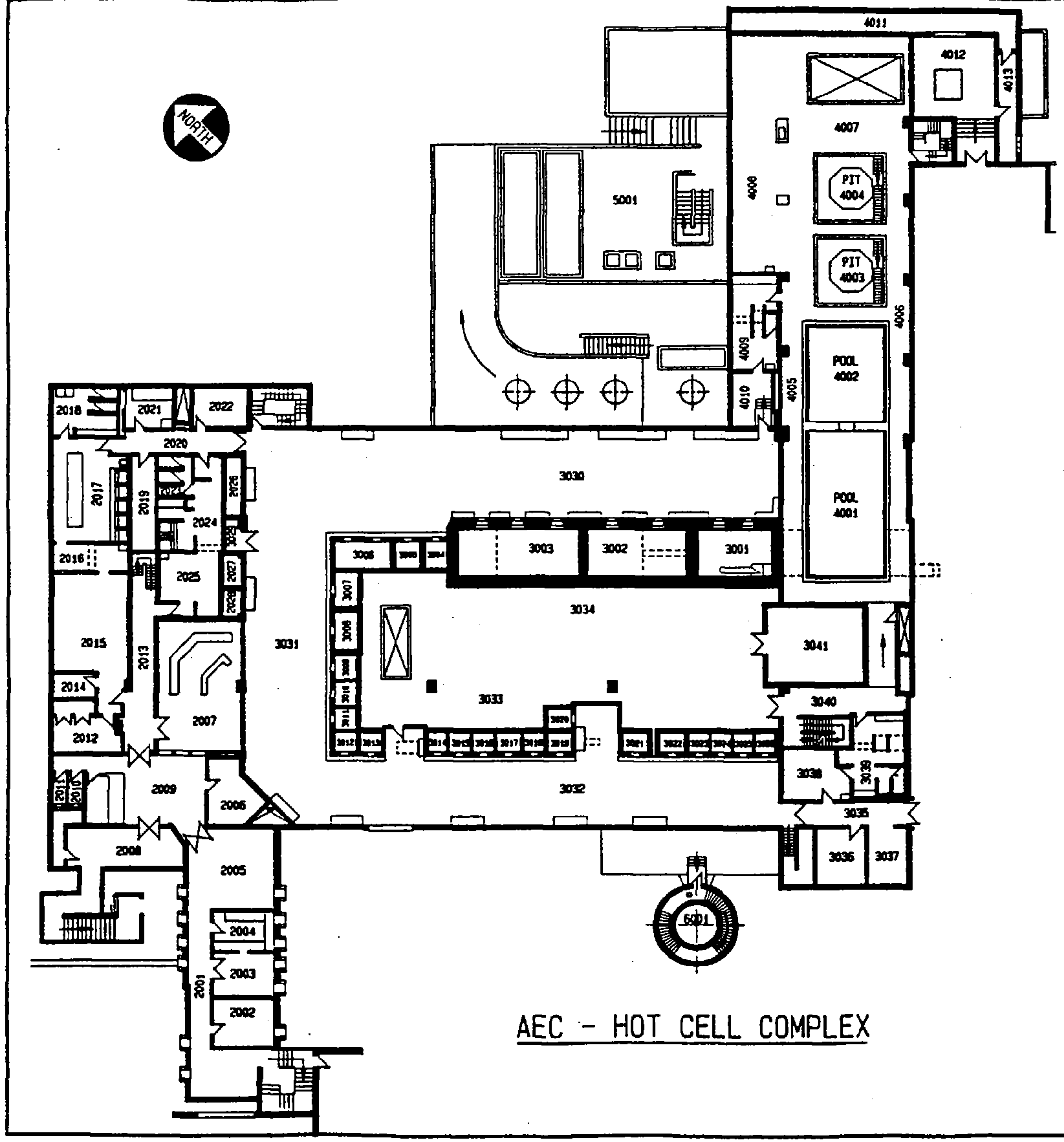


FIGURE 2



AEC - HOT CELL COMPLEX

CONCRETE CELLS

3001 CELL 1 DISMANTLING
3002 CELL 2 METROLOGY
3003 CELL 3 CUTTING

LEAD CELLS

3004 RABBIT DISPATCH / STORAGE
3005 PROFILOMETRY & HARDNESS
3006 TUBE BURST & CREEP TESTING
3007 TENSILE TESTING
3008 IMPACT TESTING
3009 GAS ANALYSIS
3010 GAS ANALYSIS
3011 GAS ANALYSIS
3012 CHEMICAL ANALYSIS
3013 CHEMICAL ANALYSIS
3014 MICROSCOPE
3015 CUTTING
3016 MOUNTING (RABBIT ENTRY 1)
3017 GRINDING
3018 POLISHING
3019 MICROSCOPE
3020 SCANNING ELECTRON MICROSCOPE
3021 DENSITY (RABBIT ENTRY 2)
3022 MOLYBDENUM
3023 MOLYBDENUM
3024 MOLYBDENUM
3025 MOLYBDENUM
3026 MOLYBDENUM

ZONE PRESSURES

WHITE ZONE = ATMOSPHERIC PRESSURE
BLUE ZONE = 25 Pa BELOW WHITE
RED ZONE = 20-25 Pa BELOW BLUE
PURPLE ZONE = 250-350 Pa BELOW RED

GROUND FLOOR PLAN
SCALE: NTS

NUCLEAR POWER - WORLD STATUS