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Mid-term report for the HTR-M & M1 Projects

D.E. Buckthorpe

NNC Ltd, UK

CONTRIBUTORS:

Framatome ANP	**F**
Commissariat a Energie Atomic `	**F**
European Directorate General Joint Research Centre	**NL**
Nuclear Research and Consultancy Group	**NL**
Forschungszentrum Juuelich GmbH	**D**
Framatome ANP (GmbH)	**D**
Empresario Agrupados Internacional s.a.	**E**

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Mid-term Report for HTR-M & M1 Projects

by

D.E. Buckthorpe

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Executive Summary

The need for reliable material data and properties is a key issue in the development of any innovative reactor technology and is especially important for those areas where safety considerations are uppermost. The HTR-M project deals with the selection and development of materials for the vessel, high temperature components and the graphite core. The project includes specific experiments on selected materials, including irradiation tests on vessel weldments and graphite. The aim of the HTR-M & M1 project is to provide a materials platform on which to develop the future HTR technological basis within Europe and an understanding of the behaviour and manufacturing requirements for some of the new materials that will be needed for such developments.

The work is well advanced and essentially in line with expectations and with no significant delays in the experimental programme. The database work has developed to a stage that enables different partners to collect and write their information onto excel spreadsheets. The data assembly activity will continue throughout the remaining period of the project and periodic and final transfer of the data to Alloys-DB will be considered in the third and fourth years.

The vessel work includes a review of available information and properties on steels used in gas-cooled reactors and previous high temperature reactors. This covers existing and new and developing plants. SA 508 type steel is proposed for the insulated design of the current PBMR and modified 9Cr 1Mo steel for the inlet temperature vessel design of the GT-MHR. Available properties on both types of material are included in the database. The irradiation experiments are to be performed on welded joints under irradiated and non-irradiated conditions. Modified 9Cr 1Mo steel is used since this material has the wider applicability and most uncertainties on database and fabrication experience (with respect to HTR vessel characteristics). Procurement of suitable material and welding trials have been completed and procedures for specimen manufacture are being finalised. The planning and rig specification / manufacture for the irradiation experiments are well advanced with some nominal test conditions and proposals for the test matrix identified. The irradiation of the specimens is expected to start early next year. No overall delay in the test programme is currently anticipated.

The Work Package on high temperature materials is well advanced. A material review plus collation of property information has been done for the control Rod and turbine components (blade and disc) with special attention paid to C/C composite materials for the former. The review and database work has been used to identify candidate materials for the tests, which are currently in the stage of procurement.

Discussions have involved a turbine manufacturer (who is directly involved in the project) for the disc procurement and advice on blade materials. Testing of turbine materials in helium will require some test facility development. Designs have been initiated and preliminary work is underway in order to have the facilities ready when the materials become available. The short-term experiments are expected to start in 2003. Intermediate creep testing of material will start as soon as possible in 2002 under the HRT-M1 project in order to maximise the amount of testing time available.

The work on the graphite properties side has so far looked at the current understanding of knowledge and considered the information available in the IAEA database. References have

been assembled and formats and property requirements for the database established. The selection of graphites, in particular for the experimental programme to be performed within HTR-M1 project is also well advanced. Irradiation damage can have a significant effect on the physical and mechanical properties of graphite and the HTR-M1 project will test a small number of graphite types that are to be irradiated within the High Flux Reactor to identify such changes. Progress on this work is underway to set the characteristics of the test programme and shortlist the types of graphites and numbers of tests. The process is being done in co-operation with the main graphite suppliers who are participating in the test programme.

The work on graphite oxidation involves tests in the THERA and INDEX facilities. This work is largely complete with results available in air and steam. Measurements have been taken on the kinetics of graphite in oxygen for temperatures between 823 and 1023 K and partial pressures of between 2 and 20kPa. Measurements in steam have required some improvements to be incorporated in the test rig. Oxidation resistance of three selected Carbon Fibre Composites (CFCs) developed for the Fusion Reactor have also been measured. Experiments have also been carried out to determine the thermal conductivity of such CFC materials.

1. Objectives and Strategic Aspects

Nuclear energy is an important and necessary part of the future energy programme of Europe, which is aimed at maintaining a diversity of supply and protecting industrial and domestic consumers against the worst of the effects of fuel shortages. Within the nuclear community there is a consensus that a significant innovation potential is available within the Modular High Temperature Reactor (HTR), which can lead to increases in safety and environment protection requirements at a competitive cost level. The Modular HTR deals with many of the safety issues of other reactor types, and can be constructed in a significantly shorter period and against a significantly lower capital cost. Additionally, the high coolant temperatures, low power level and extensive siting possibilities offer the prospect of entering other energy markets, e.g. co-generation, process heat, hydrogen generation, district heating and desalination.

The technologies of gas-cooled reactors (GCR) and especially HTR were mainly developed in Europe over the past 40 years. Considerable experience is still available representing unique fields of competence on a worldwide comparison. The United Kingdom has vast experience with graphite-moderated reactors and Advanced Gas Cooled Reactors. German and UK organisations have experience with predecessor models of HTR, French companies of elevated temperature reactor component design capabilities. The Dutch organisations have been exploring the possibilities of small HTRs for co-generation for several years, and Belgian, Spanish and Italian partners also have their specific experiences, interests and capabilities in the elevated temperature reactor field. On a national level, participants can only progress on certain parts of the Modular HTR system. By collaborating within the EU Fifth Framework Program individual contributions are significantly enhanced and each in turn has access to a very comprehensive ongoing programme. The European Modular HTR program supported by the 5th Framework Programme is recognised internationally as one of the leading development initiatives in HTR technology.

The development of an advanced HTR concept in Europe requires an established platform of materials knowledge and understanding on which future evaluation of any potential technological developments can be made. Information is required on material behaviour under representative reactor operating conditions for the main steel and graphite structures and those important to the safety. Such information is a fundamental requirement for assessment of feasibility and assurance of integrity. The global objectives of the HTR-M & M1 projects are aimed at providing these materials data for the key components to support the development of High Temperature Reactor technology in Europe.

The Reactor Pressure Vessel (RPV) is an important safety component and key information on candidate materials under HTR relevant conditions is not available. Information is lacking on the effects of irradiation and environment particularly for the welds. For the RPV the integrity of the welded joints is seen as a particularly important feasibility issue and related properties are needed on manufacturing of products and parts, behaviour of welded joints and the influence of environment (neutron-irradiation fluence, operational temperature, and helium environment). The main concern is the ability to resist cracking which may give rise to leakage and failure from fracture and fatigue processes. RPV materials are needed for operation both within the creep and non-creep regimes. Cooling enables RPV temperatures to be kept below creep temperatures (370^{o}C) under steady operating conditions allowing PWR type steels to be used. Non-cooled designs operate at higher temperatures (450^{o}C) for long periods and therefore require higher strength steels. The objective of the HTR-M &M1 work is therefore to investigate and confirm the choice of candidate material options for different HTR concepts, in relation to both normal and accident conditions, and to compile their design properties. In particular specific tests on specimens from welded joints are to be performed under irradiated and non-irradiated conditions.

The high temperature areas of the reactor and power circuit operate at temperatures from 600°C up to 850°C and above in order to reach high energy levels of efficiency. For such components a number of high strength metallic and ceramic materials are required in order to provide a basis for reliable operation. For such materials, some data exists but the information and experience are not well established for the HTR environment. The structures to be investigated include the control rods and the turbine. For the former, carbon-carbon (C/C) composites provide an option for which some work is to be performed. For the turbine (disc and blades) high alloy steels are possible although the expected working conditions and environment conditions are considered beyond current industrial experience (issues of endurance rather than temperature). A key issue is the impact of environment both with regard to chemical processes that can give rise to significant material property strength reductions and choice of composition affecting activation of alloying elements.

The need for reliable graphite data is seen as a crucial issue for existing and new HTGR projects in Europe and is an important requirement for future decommissioning activities. The graphite core is a key component that affects safety and operability of the reactor. Its performance is critically dependent on the graphite properties, which are irradiation dependent. The most important considerations are component integrity and changes in core geometry, both of which are affected by the dimensional change. Many of the graphites used in previous core designs are no longer available. The main questions are on the availability of the coke and manufacturing procedure. Specialist information and experience is scarce and most of the European experts familiar with the past and the existing sources of information have retired. The situation is made more acute because of the scarcity of high flux reactors to perform any new testing. New data is needed for current grades of graphite as well as for comparative assessments with previous data to assess consistency and suitability.

The comparatively small oxidation resistance of graphites at high temperatures also requires special attention due to its relevance for safety analyses of air and water ingress accidents, licensing procedure and normal operation. An important assessment is the consequences of severe air ingress. The provision of sufficient tools for future analyses on the HTR key accident 'core burning', where lack of knowledge on experimental data on chemical kinetics was detected by former accident analyses are addressed. Also the development of ceramic protective coatings as an option for future advanced fuel and reflector graphites are explored. Experimental and theoretical examinations of graphite oxidation in normal operation of the direct cycle HTRs including catalytic oxidation and oxidation induced strength loss will be investigated, saving and improving the existing knowledge in this field. Development work on promising advanced carbon-based materials for HTRs with respect to their oxidation resistance will be contributed in collaboration with similar work on first wall materials for fusion reactors.

3. Scientific and Technical Assessment

The HTR-M & M1 project work programme is split into three areas according to the type of materials and conditions experienced:

- Reactor vessel
- High temperature areas (control rod and turbine)
- Graphite structures including oxidation

The following sections provide a scientific and technical assessment of the results achieved at the mid way point in the projects.

3.1 Reactor Vessel

This work, which is contained within Work Package 1 of HTR-M involves the following packages of work;

- review existing materials used in gas-cooled reactors and previous high temperature reactors,
- setting up a materials database on design properties (which will lead to identification of data omissions for future R& D testing),
- carrying out of specific tests on welded joints under irradiated and non-irradiated conditions.

The project resources allow one type of vessel steel to be irradiated. For the tests a recommendation is made, depending on operating conditions, data omissions and available property and fabrication details.

The work is performed within a series of defined tasks (HTR-M-D-1.0.15). The results are summarised below together with details of progress and assessment of results.

Task 1 - Review of RPV materials and design

(i) Material Review

The RPV, which forms part of the pressure boundary system contains the helium coolant by maintaining the boundary integrity. It provides structural support and alignment for the components within it (core and core support structures). The material review work has considered developing reactors (HTR-M 01/9 D.1.1.9) as well as experience from other reactor systems. Two types of materials are currently used for RPVs, depending on the temperature of the pressure boundary under normal operation or design conditions. The designs of future plants make use of either SA 508 steel for insulated vessels or modified 9Cr 1Mo steel for ‘inlet temperature vessels’ (see table 3). These materials have similar strength levels at temperatures up to 370°C. The use of modified 9Cr 1Mo steel allows higher temperatures with only a gradual reduction in design strength at temperatures up to 450°C. Above 450°C allowable stresses for all materials fall off rapidly (Fig. 1).

The economic competitiveness of the reactor is a major consideration and factors such as fabrication costs and weight are important. A preliminary investigation (HTR-M 01/10

D.1.1.17) suggests for a HTR sized pressure vessel made from SA508 type steel, the vessel may be up to 10% heavier than a modified 9Cr 1 Mo steel vessel, but costs around 35% less. Adoption of forming rather than forging (if conditions allow) may reduce the cost difference to 20-25%. The review confirms SA508 type steel as a viable candidate for the "cold" (current PBMR) HTR vessel design.

A further potential candidate for a "warm" vessel steel was 12Cr recently adopted in Japan for Fast Reactor steam generator applications. The steel has been used extensively in steam plants in Europe, usually at temperatures up to approximately 540°C, however welding of the material is more difficult, in particular careful control of temperature is required during preheat, interpass and post weld heat treatment. Some thick section components have been made but most of the service experience relates to thinner sections (pipes, headers). The strength of both 12Cr and modified 9Cr steels reduces significantly as section thickness increases and although 12Cr has a slightly higher strength (10%) below 500°C (where the design is governed by short term tensile properties) above approximately 500°C creep behaviour is more important, and here modified 9Cr 1Mo steel has superior creep strength.

The main concerns with regard to structural integrity are at the vessel welds. These have to satisfy the safety analysis methodology and safety studies (defect location and defect size) and have to be assessed from the point of view of non-destructive examination and potential for failure or leakage (HTR-M 01/11 D.1.1.18). The main damage mechanisms (HTR-M 02/2 D.1.1.27) are fracture, fatigue and creep-fatigue (depending on temperature). The test programme and its development addresses toughness and creep properties under as-fabricated and simulated end-of-life conditions and will provide an understanding of the welding processes, weld metals and post-weld heat treatment required for thick welds and weld factors to be applied on the base material properties. Other sensitive zones that are important are thicker sections (potential for reduced properties and strength), hot spots and regions important from a functionality point of view (HTR-M 02/2 D.1.1.28). This includes the flange area and belt-line that have to satisfy primary and secondary stress limit requirements and progressive deformation mechanisms.

In China silicon killed C-Mn steel to ASME SA 516-70 has been specified for both the HTR 10 test reactor and a future power reactor. This material is similar to the C-Mn steels used in the UK for the construction of both steel and concrete pressure vessels in CO_2 cooled reactors of the Magnox and AGR types. Long term operating and/or design temperatures are limited to 370°C. Similar limits apply to the SA 508 forgings used widely in LWR pressure vessels and proposed for pebble bed reactors of approximately $300MW_{th}$ in both South Africa (PBMR) and Japan (HTR-GT 300). It should be noted that the SA 508 specification covers a number of grades, some of which are not suitable for pressure vessels. In terms of the current designations in ASME specifications 'SA 508 type' material is taken hereafter to mean SA 508 Grade 3 Class 1 or the equivalent material in plate form SA 533 Type B Class 1. Equivalent European designations are 20Mn Mo Ni 5 5 (Germany) and 15MND 5 or 18MND 5 (France). Except for HTR-10 the above systems have core inlet gas temperatures close to 550°C so the integrity of the RPV depends on the performance of insulation provided by fibre blanket and / or stagnant layers of He. Preliminary considerations suggest that levels of primary membrane stress have been set on a conservative basis when compared with a large (1100 MW) PWR vessel such as Sizewell B.

In both the HTTR test reactor and larger power reactors of 450-600 MW_{th} the RPV temperature is close to the core inlet temperature due to the use of inlet (or intermediate) temperature helium to cool the inside surface of the vessel. Vessel temperatures are in the range 395-460°C under normal operating conditions. An initial comparison suggests that the HTTR inlet temperature of 400°C permits the use of 2¼Cr 1Mo steel with margins of approximately 25% on allowable stress and approximately 40°C on temperature. Modified 9Cr 1Mo steel has been specified for both large and small reactors with the belt-line region of the vessel running at the core inlet temperature. This material is not yet qualified for pressure vessel use according to most design codes (HTR-M 02/8-D-1.1.40). The RCC-MR design rules for steam generator tube material in modified 9Cr 1Mo steel were extended during the European Fast Reactor (EFR) project to cover its use for tubeplates, shells and hemispherical ends in steam generators with outlet steam temperatures near 500°C. Comparison of estimated primary stress intensity values for GT-MHR with EFR values of S_{mt} show a close consistency. It should be noted however that Russian design rules use different factors in deriving design stresses from specified mechanical properties and therefore may not indicate the same level of similarity.

From the candidate material grades for HTR pressure vessels (HTR-M 02/4-D-1.1.31) important conclusions are reached (HTR-M 02/4-D-1.1.41) with implications for the current and future HTR-M programme.

- Long term creep data are required at moderate temperatures (425-500°C) to confirm design values for 2¼Cr 1Mo and modified 9Cr 1Mo steel.
- It is desirable for acceptance and design using the candidate grades to ensure that normal service temperatures are below limits ranging from 371°C for C-Mn and Mn-Ni-Mo grades to 435°C for modified 9Cr 1Mo steel. These limits arise in part from uncertainties concerning the long term creep strength of 2¼Cr 1Mo and modified 9Cr 1Mo steel.
- In addition to the service temperature limits, an increased thickness is necessary for vessels in 2¼Cr 1Mo compared with Mn-Ni-Mo or modified 9Cr 1Mo steel vessels. A thickness increase of approximately 25% is required for quenched and tempered grades and approximately 50% for normalised grades of 2¼Cr 1Mo steel.

Although high toughness values can be obtained in all the grades, toughness data to provide assurance of resistance to non-ductile failure is reasonably complete only for Mn-Ni-Mo grades. Additional toughness data including the effects of irradiation and thermal ageing are required particularly for modified 9Cr 1Mo steel and for normalised and tempered grades of 2¼Cr 1Mo steel. HTR involves new requirements for the provision of base materials and their fabrication even in LWR grades. Difficulties increase with alloy content. A particular problem has been the optimisation of weld filler metal for modified 9Cr 1Mo steel. Creep strength requirements are unlikely to involve very penalising stress reduction factors provided that the temperature limits for normal operation are adhered to.

(ii) Environmental considerations.

a) Compatibility

The above rationale for materials selection in terms of design stresses does not take account of any additional material thickness required to allow for the effects of the He environment.

HTR gas chemistry is dominated by the impurities H_2, H_2O, CO and CO_2. Low concentrations of H_2O and H_2 are produced by leakage and / or de-sorption from both metal surfaces and graphite. CO, CO_2, and CH_4 may be produced by coolant / graphite reactions at high temperatures. Three factors will therefore control the He impurity levels.

- The hydrogen and oxygen supply rates.
- The core temperature and gas residence time, the latter is usually considered to be sufficient for equilibrium to be achieved at 850 - 1000°C.
- The capacity of the gas clean-up plant.

Information on He impurity levels has been gathered from various sources and thermodynamic assessments have been made for these atmospheres with the results of the assessments in terms of the carbon activity and oxygen potential (notional partial pressure of oxygen) introduced on to phase diagrams for Iron and Chromium. Points were included for identified cases and typical AGR gas compositions and results at temperatures relevant to PBMR and GT-MHR were also considered.

The work concluded that the metal losses due to the He coolant is not due to the formation of oxide scales but to the effects of carburisation in cold wall vessels or decarburisation combined with internal oxidation in warm wall vessels. The kinetics of these processes determine the effective metal loss. However given a belt-line wall thickness in the range 140-200 mm metal loss will only become significant if unstable processes such as breakaway corrosion or metal dusting can occur. Comparison with AGR experience shows the former is not a credible threat in HTR He, however long term carburisation of cold wall material leading to metal dusting cannot be excluded on thermodynamic grounds. In this case kinetic data are required to evaluate the threat to vessel integrity. If the metal dusting problem is judged to be a threat at cold wall temperatures then an approach based on control, maintaining equilibrium values of oxidation potential, should be considered. Overall except for the possibility of carburisation at cold wall vessel temperatures, coolant compatibility issues are not expected to have a strong direct impact on materials selection because metal loss allowances will be a small proportion of the pressure vessel wall thickness.

b) Irradiation & Ageing.

A review of available information on the effects of irradiation and ageing embrittlement has been made for different RPV steels. The work was aimed mainly at modified 9Cr 1Mo steel (HTR-M 02/11 D 1.1.48) as this was considered the main candidate for the tests (see (c) below). The review considered the effect of dose and temperature on the ductile brittle transition temperature (DBTT) and the upper shelf energy (USE) both commonly used to evaluate the potential effect of irradiation on RPV steels. The expected dose and temperature range for the HTR vessel was expected to be in the range of 8-20mdpa and 350-450^{o}C.

The review showed that there were no data available for modified 9Cr 1Mo at the expected HTR conditions. All of the data for modified 9Cr 1Mo data were obtained at much higher doses (>0.8dpa) though lower doses were available for other steels. The review suggested that the irradiation effects in modified 9Cr 1Mo steel at temperatures 400-450^{o}C would be small and irradiation at 350^{o}C would give a rather larger effect.

The effect of thermal ageing over the lifetime of the HTR vessel (400,000 hours at 400-460°C) on the properties of wrought modified 9Cr steel is also expected to be small. However no data are available for the effect of thermal ageing on modified 9Cr weldments. Information from studies of LWR steels indicated that thermal ageing embrittlement in the coarse-grained heat affected zones of welds can be significant. Significant effects of irradiation or thermal ageing in pressure vessel steels have in the past been associated with levels of critical elements (P, Cu, As, Sn, Sb) that are high by current standards. It is anticipated however that HTR-M test welds will have relatively low levels of the critical elements even outside the beltline region and therefore will not be subject to either irradiation or temper embrittlement of the severity that has caused concerns for LWR integrity in the past.

At HTR warm vessel temperatures of 400-450°C, thermal ageing can produce measureable increases in the DBTT of simulated coarse grain heat affected zone material. The HTR-M irradiation studies provide the opportunity to assess the possible threat for thick section modified 9Cr 1Mo weld made with a relevant process. Control specimens for the irradiation experiment can provide some relevant data. If possible additional material should also be made available for long term ageing at temperatures in the range 450-550°C. A further test (e.g. in the 6th Framework Programme) could then make use of the aged material to make comparisons with previous studies and to provide preliminary guidance on performance under HTR conditions. The review recommends that the effect of thermal ageing on modified 9Cr 1Mo weldments should be investigated further.

(c) Material selection

The existing LWR pressure vessels in SA 508 and its European derivatives are considered to encompass the conditions in the “cold” (current PBMR) HTR vessels with respect to operating temperature, wall thickness, design features (thick flanges etc.) and irradiation levels. The large database and the extensive fabrication experience from LWR programmes should provide a sound basis for such an HTR vessel design. The most obvious gap in data however relates to possible transients involving temperatures above the usual LWR limit of approximately 370°C. Of importance is whether the temperatures are close to any metallurgical (heat treatment) limits of the material. A substantial database and fabrication experience exists for CO_2 cooled reactors in the UK, with respect to C-Mn steels similar to the SA 516-70 grade specified in Chinese designs. There is also European experience of complementary high temperature materials (2¼Cr 1Mo grades). It is considered therefore in general that there should be relatively few problems in assembling an adequate database extending to temperatures involved during transients.

The above considerations and the state of the art review (HTR-M 02/11 D-1 1 49) confirm that modified 9Cr 1Mo steel as having the most uncertainties as to the available database and fabrication experience with respect to HTR vessel characteristics. This material also potentially has the wider applicability and since for the Framework Programme it is only possible to test one material within the High Flux Reactor this represents the most likely candidate for the experiments. The extent of testing of control specimens is expected to cover as received (welded and post weld heat-treated) and irradiated material (irradiation time approximately 100 - 200 hours). Thermal ageing effects in 40 years at 450°C may be significant but useful experiments may not be possible within the time scale of HTR-M.

Task 2 - Establishment of Database

One of the main objectives of the HTR-M project is the development of a database of materials information for the key components of the High Temperature Reactor. For the Reactor Pressure Vessel the results of the above review have identified the vessel steels to be included in the materials database for design and feasibility investigations. The most likely candidates are those considered for existing and new reactors, i.e. SA 508 (and its European derivatives), SA 516-70 grade specified in Chinese designs, 2¼Cr 1Mo steel and modified 9Cr 1Mo steel.

The database jointly covers vessel steels, high temperature alloys and graphites. The overall layout of the database was discussed in a preliminary document outlining its aims (HTR-M 01/03-D-0.0.21) and format (HTR-M 01/3-D-0.0.22). The overall layout covers material designation, provisions, products & parts, test data and design property information (HTR-M 02/11-D 0.0.50). The materials vessel database in excel sheet format is contained in HTR-M 02/11 D 0 0 51. The design property information is one of the main outputs from the database and is expected to help drive future decisions on information needs and tests. Design needs plus omissions and shortage of test data is expected to be the basis on which the database will be built up and expanded.

The Alloys-DB system developed at JRC for high alloy steels is being considered as a future potential for housing the information on the web. A PC version of Alloys-DB has been provided to NNC for assessment of the program and its suitability for this purpose and suitable agreements to allow access by all the HTR-M participants drawn up by JRC.

Task 3 - Weld production and testing

The reference material selected for the irradiation tests was modified 9Cr 1Mo steel. The test pieces are to be taken from representative thick section welds using narrow gap TIG with a double V weld preparation produced by Framatome. The procurement of sufficient material for manufacture of the vessel weld features was made by Framatome and a reduced phosphorus filler material was selected and purchased for the fabrications from the producer Kobe steel. This was successfully used by Framatome in the past for producing 30mm thick welded joints with a large range of welding parameters and considered the best available for the application.

The first pilot test welds (150 mm thick) showed a significant number of micro-cracks (24 over an area of 6600mm^2) in the weld metal. These cracks (< 0.3 mm) were not detected using the usual X-ray or ultrasonic examination but seen when performing a metallurgical examination. The shape of the cracks indicated hot cracking. This was not expected as the selected filler had the lowest tendency to hot cracking among the products tested by Framatome. The fabrications were repeated using a lower energy and although there was a significant reduction the problem was not solved completely. The number of micro-cracks was reduced to 5 (see fig. 2). Changing the welding parameters further was not considered a viable option since the tests would need to mirror industrial practice as far as possible. Following discussion (Ref. 4) and recognising that procurement of a new filler material would take the best part of a year and that there would be no assurance of success or that a new filler would be available commercially, it was agreed to adopt the Kobe filler with reduced energy for the tests. It was expected that the HAZ would be defect free and the density of the cracks in the weld metal allow machining of defect free specimens to be achieved. A procedure for identifying cracks and machining and checking of test pieces is being developed in co-operation with JRC. Characterisation trials should begin as soon as newly fabricated weld test pieces have been produced by Framatome.

It was recognised that this work represents the first trials in this material for such thick section vessel type welds and considers only one geometry. These tests therefore represent a first step in confirming the fabrication parameters for such an application. Later developments in the fabrication procedure will include forged parts. A preliminary assessment of a suitable test matrix and initial proposal for the test conditions has been made (Ref. 4) by NRG. The final conditions and timing are to be set following confirmation of test piece analysis and reactor availability.

A close co-operation between JRC, responsible for reference tests, and NRG, performing the post-irradiation testing, has been initiated to ensure testing practices, especially for fracture toughness testing, are kept similar. NRG are to perform the post irradiation tests and JRC identical reference tests for non-irradiated specimens using the same testing procedures. Proposals for sampling have been discussed and it is considered that the weld geometry will provide sufficient material for test specimen fabrication. With regard to test temperature and duration this will, as far as possible, be based on relevant conditions for PBMR and / or GT-MHR with irradiation doses and temperature chosen to give maximum benefit with regard to data omissions and design / component application. It is expected that temperatures of 350-450^{o}C and irradiation doses between 10-20 mdpa will be adopted.

With regard to the final selection of the test matrix this will be controlled by budget limits. The irradiation rig can accommodate high numbers of test specimens. The fracture toughness specimens will be of limited dimensions, considering the materials properties to be expected after irradiation, nevertheless they will occupy most of the LYRA-rig space.

3.2 High Temperature Materials

This work, which is contained within Work Package 2 of HTR-M (HTR-M 01/9-D-2.0.10) and Work Package 2 of HTR-M1 involves the following areas of work.

<u>Control Rod</u>

- ♦ Review design requirement and potential materials for the HTR control rod with emphasis on C/C composites. List available properties for inclusion in the database.
- ♦ Set up a materials database on design properties (which will lead to identification of data omissions for future R& D testing).
- ♦ For a C/C composite material, carry out some specific tests to assess non irradiated properties.

<u>Turbine materials</u>

- ♦ Review available materials for application to turbine discs and blades.

- ♦ Set up a materials database on properties (which will lead to identification of data omissions for future R& D testing).

- Select reference materials and perform short term and medium term tests under HTR relevant conditions representative of the He environment and temperature.

3.2.1 Control Rod

Task 1 - Design Specification

A report on the design use and specifications (HTR-M 01/7 D.2.1.14) was issued for the control rod. The report contains information on the function, geometry (control rod plus core) and typical transient and operating conditions based on information available from the PBMR and GT-MHR. For the GT-MHR, the transients are separated into five categories and envelope values for the temperatures in the helium gas in each of these categories have been defined. Information on maximum heat release in the structural material and rod absorbent is also given together with considerations for seismic, He impurity content and neutron fluence. For the PBMR the main information is on the system, function and geometry.

As a first assessment the operating conditions of the GT-MHR were expected to bound the overall requirements and have been used to assess requirements. The information will be expanded as more detailed information on PBMR and GT-MHR becomes available.

Task 2 - Material Review

For some of the non-graphite internal components (core support plates, grids) austenitic and ferritic steels can be used. In general, operability and applicability up to temperatures of 550^{o}C have been firmly established for such materials within projects such as the Advanced Gas Cooled Reactor in the UK, the European Fast Reactor Project and High Temperature Reactor Projects such as AVR. At higher temperatures nickel based and Fe-Cr-Ni Alloys are available and for HTR which has the additional effect of a helium environment the PNP and Japanese He/He exchangers provide some important experience. For even higher temperatures and irradiation levels C/C composite materials provide increased thermal resistance offering improved reactivity control during shutdown and in the longer term could allow the normal operating temperatures of future reactors to be increased.

In a first attempt to clarify the needs for such materials, a review document (HTR-M 01/9 D.2.0.12) was prepared which looks at the experience of the Japanese HTTR and the R&D test work performed at JAERI on C/C composites. The base material considered for the HTTR control rod was alloy 800H and use of this material meant that it had to be inserted in two steps to avoid damage by high temperature (>800°C) and irradiation in the HTTR core. JAERI have subsequently considered a C/C composite control rod based on a carbon fibre weaving technique (which provides strength in the circumferential, axial and radial directions). The most recent located article suggests non-irradiated data on two grades of C/C composites have been evaluated at JAERI. Initial tests have shown a stable fracture behaviour and high strength compared with metallic alloys. Irradiation tests on these materials are planned from 2005.

A more detailed state of the art review considers published information for alloy 800 and 18 C/C materials (HTR-M 02/6 D.2.1.36). The review compares available properties in the non-irradiated and irradiated conditions. As with graphite significant changes in the properties occur due to the effect of irradiation and temperature. Most of the published information deals with thermal behaviour available from tests in support of Fusion applications. Figure 3 shows the effect of irradiation on thermal conductivity for one composite material, indicating a significant reduction at room temperature and less of a reduction at higher temperatures. It was also clear that as with graphites that there were variations between different types of composites, which makes the transfer of properties from one type to another difficult.

Task 3 – Database

The review work identified a number of potential materials that can be included in the database. Tabulated values are given (HTR-M 02/6 D.2.1.36) to provide a starting point for assembling relevant information. As with graphites, the most useful data is expected to come from specific tests under irradiated conditions. Such tests on the chosen material is however outside the scope of the current HTR-M programme.

In the short term the tabulated information can also provide a preliminary assessment of properties. In the long term together with specific test results the information should help lead to a better understanding of the behaviour of such materials for control rod application. Information on the oxidation of composite materials has been investigated for air ingress accident conditions (see section 3.4.2) and these results are also to be included in the database.

As with the vessel steels, the material information is to be assembled throughout the project and collated onto one central set of spreadsheets for use by all within the project. The Alloys-DB system developed at JRC for high alloy steels is being examined to see if this offers the potential for housing the information within a secure package and for making the information available through the web.

Task 4 – Material procurement and testing

For the tests, a supply of C/C composite material is needed in cylindrical form with dimensions representative of a typical HTR control rod cross section. Procurement of suitable material proved difficult within the budget figure set for the experimental programme. Following discussions with the graphite manufacturer SGL, who are providing material for the graphite irradiation tests, a suitable supply of material has been secured, and steps are now in hand to finalise the test programme.

3.2.2. Turbine Materials

Task 1 - Design Specification

A report on design use and specifications for the turbine (HTR-M 01/7 D.2.1.19) has been issued on SINTER. Typical transient and operating conditions are reviewed based on information available from the PBMR and GT-MHR. Information is sparse and as with the control rod specification document the contents are to be expanded to include more detailed information on PBMR and GT-MHR as it becomes available and as the project develops.

Task 2 - Material Review

The review considered eight potential materials for the turbine disc, thirteen for the blade (including the Russian backup options) and three structural materials for the stator and ducting, etc. Creep resistance and high temperature strength were important requirements and expected to be a main selection criterion (HTR-M 02/7-D-2.1.39).

The turbine components, especially the turbine discs and blades are required to operate at high temperatures (850-900 ^{o}C) and with long endurance times (60,000 h) to minimise the maintenance periods. The key areas are the first stage turbine discs and blades and performance and integrity are affected by cycle temperature and maintaining critical dimensions (clearances) throughout the service life. The main criteria to be considered are creep and the influence of the environment.

For turbine discs there is a requirement to limit the permanent growth and distortion to within typical design life targets. Critical regions for the disc are the hottest parts (e.g. the disc neck because of unrelieved high-localised stresses, and at the rim, due to the additional geometric effects of the blade root slots and possibly cooling holes).

For the turbine blade failure modes such as creep, high cycle fatigue and low cycle fatigue have to be taken into account. The gas radial temperature variation often peaks typically in the middle third of the blade with steep temperature gradients across the blade section that vary according to the transient and steady state conditions. All regions of the blade profile therefore undergo complex stress-strain cycling with reversed plasticity in some areas.

The review considers the merits of the available materials by considering their composition, the manufacturing processes and available properties. The main findings and resulting assessment are discussed below.

(i) Turbine discs

Possible candidate alloys for the disc include A286 (Cr Ni Fe), IN706, IN718, UDIMET 720 and MA6000 (an Oxide Dispersion Strengthened (ODS) super-alloy).

The material used for the disc needs to have a sound industrial base and be capable of production of large defect free ingots with good forging properties and proven thermal stability (HTR-M 01/3-D-2.0.23). Manufacturing considerations are a major factor. To produce large ingots without porosity and segregation requires the production of a 10 ton ingot with subsequent forging. For aero-engines re-melting technology (vacuum induction melting, vacuum arc re-melting, electro-slag re-melting) is used to produce large diameters, however, with current alloys, discs produced in this way have reached the limit of their performance. The availability of large diameter hipping furnaces (~1.4 m) has meant that powder metallurgy using Hot Isostatic Pressing (HIPping) is a possible manufacturing route. This can yield high quality ingots and near finished sized components suitable for turbine discs. HIPping produces materials with design properties different from those of the corresponding forged or cast alloy and subsequent heat treatments can significantly change the high temperature strength properties.

Discussions with turbine materials manufacturer Aubert & Duval identified UDIMET 720 as the best available candidate. This can be processed by powder metallurgy and HIPping. Although the literature search showed very few published data on this material the operating temperature for UDIMET 720 is thought to offer the highest at around 700^{o}C (which suggests that a non-cooled disc operating at 850^{o}C may be too ambitious). IN706 on the other hand operates successfully at temperatures of 600^{o}C (steam turbines) and IN718, a further possible material, is near to commercial production but R& D is still required in order to control the grain size. Of the several materials examined only the oxide dispersion strengthened (ODS) material (MA 6000) looked capable of providing greater strength at higher temperatures (Fig. 5), but its manufacturing route still requires significant work.

(ii) Turbine blades

From the blade materials investigated the best potential long term creep strength was provided by the Molybdenum based alloy TZM. This has seen a significant amount of testing within the German HTR programme but its high a ductile brittle transition temperature appears to make it a less practical option compared with Ni based alloys. The most promising Ni based super alloys in terms of creep strength are the single crystal alloys PWA 1483 (Cr-oxide former) and CMSX4. PWA 1483 (an Al-oxide former). For the direction solidified blade suitable materials would be DS IN 792 LC (Cr-oxide former) and CM 247 LC DS (Al-oxide former). In the case of a conventionally cast blade (which could be used if the blade was cooled) IN 792 (Cr-oxide former) and MAR M247 (Al-oxide former) are possible candidates (HTR-M 02/4-D-2.2.32). Figure 4 shows the 60,000 h creep rupture strength of some Ni based blade Alloys.

Single crystals offer the highest creep properties but their cost is high, properties can be an-isotropic and they cannot be easily repaired if damaged. Directionally solidified blades on the other hand are good candidates for non-cooled blades. They offer improved creep properties compared with conventionally cast versions, better repair possibilities and their experience in industrial land-based gas turbines is more extensive. Conventionally cast grades are easy to procure, have extensive industrial experience and the fabrication of HTR blades should be possible, however, their major limitation is the modest creep strength at 850°C.

(iii) Effect of environment

The effect of impurities within the helium environment is a critical issue that affects both the blades and the disc. A concern is the effect of corrosion on strength. Corrosion can cause a significant shortening of the material creep life and acceleration of creep crack growth rates. Below 577^{o}C corrosion of such alloys is limited. Between 577 & 900^{o}C chromium rich oxide scale can form also carburisation and de-carburisation due to chemical action. The corrosion resistance of alloys in HTR helium depends on the levels of minor reactive elements as well as the main alloy constituents. The environment in a HTR is composed of helium with impurities as CH_4, CO, H_2O and H_2 at μbar levels. Depending on the partial pressure of the impurities, the atmosphere can be either oxidizing (high P_{O2}, low a_c) or carburising (low P_{O2}, high a_c) for the alloys selected. The potential for carburisation or decarburisation is an important material selection criterion. Carburisation can be limited by a protective Cr oxide layer provided that the oxygen partial pressure is sufficiently high for a stable Cr oxide scale to be formed. However experience from the past German projects has shown that the oxygen partial pressure may not, in all cases, be high enough for the formation of a stable Cr-oxide scale. In such a case Al oxide formers should be considered since Al oxide forms even at extremely low oxygen partial pressures.

(iv) Coatings

Coating of the blades may be necessary for long life. A base material with adequate corrosion resistance is still however needed even in the case of a coated blade. Application of suitable coatings can arrest creep reduction tendencies, but their use requires an understanding of the potential for interfacial cracking at the coating layer to avoid the development of more significant cracking from the interface. Coating must however be of the same type (chromium oxide former or aluminium oxide former) as the base alloy. For turbines aluminide coatings have been developed for resistance to oxidation. Metal, chromium, aluminium and ytrium coatings (MCrAlY, metal M being nickel, cobalt or iron) are used for hot corrosion. Thermal Barrier Coating (TBC) involving a second porous coating can be used to give an additional temperature advantage (of up to 100°C). Deposition of such coatings is usually done using vapour deposition (EP-PVD) or plasma spray. The choice of the best coating remains to be made in the 6th Framework Programme for HTR helium environment and its durability assessed.

(v) Alloying elements

The presence of alloying elements in the materials e.g. cobalt (which is in most of the currently available turbine disc and blade materials) is a further area of investigation. The main issues are the potential for plate out and lift off of particles and their activation and prevention of them flowing through the core. The current view however is that the amount of Co present in the alloys should not present any serious drawbacks towards selection. In the case of a coated blade the alloying elements in the coating are important and should be confirmed for suitability.

Task 3 - Database

The materials chosen for inclusion in the database are to be taken from the list of materials considered in the review (HTR-M 02/7-D-2.1.39). The literature review identified information on tensile, creep and fatigue strength plus results on fracture / crack growth behaviour. Information on physical properties (Young’s Modulus, conductivity, etc.) was limited. No information was found for turbine disc and blade materials subjected to low levels of irradiation.

Unlike the vessel steels turbine materials are not covered by established design codes and the material property assumptions used for designs are developed largely from turbine operating experience. The HTR turbine application is outside current industrial experience (issues of endurance rather than temperature) and additional margins are likely to be necessary in order to assure the required level of reliability.

As discussed above, the Alloys-DB system developed at JRC for high alloy steels is being examined to see if this offers the potential for housing the information.

Task 4 - Experimental programme

The choice materials selected for the short and medium experiments of HTR-M & M1 were as follows:

Turbine disc:	UDIMET 720
Turbine blade:	IN 792 DS
	CM 247 LC DS

The test information gained during the HTR-M & M1 project are to be included in the database. For the turbine blade tests direction solidified chromium former and aluminium former materials have been chosen. The current view is to avoid single crystal materials if possible at this stage in the development.

Procurement of these materials is in hand. A large pancake of UDIMET 720 has been bought with delivery expected towards the end of 2002. Procurement of the blade materials proved difficult initially because of the small quantities involved however a supplier for the materials has been located.

Information on the test programme and planning for the tests has been reported for HTR-M (HTR-M 02/6-D-2.2.35) and HTR-M1 (HTR-M1 02/9-D-1.1.7). Since the impurity levels are unknown it was decided to test under extreme carburising and decarburising conditions, exposing the specimens before testing to different environments to gain information on the likely strength variations expected. An argon atmosphere could then be used for the tests. The tests are to be done covering four cases.

- Air, as received.
- Fully carburised.
- Fully decarburised.
- Heat treated with carburising and decarburising.

Characterisation tests and preparations for commencing the short and medium term tests will commence as soon as supplies of material become available.

3.3. Graphite Materials

This work, is contained within Work Package 3 of HTR-M (HTR-M 01/10-D-3.0.20) and Work Package 2 of HTR-M1 and involves the following areas of work.

- ♦ Review past and current grahites and available properties and assemble within a database for application to HTRs.
- ♦ Perform oxidation tests on graphites and advanced carbon based composites for air ingress accident conditions.
- ♦ Carry out tests on selected graphites to determine properties under irradiated conditions.

The following sections provide a summary of progress and results to date.

3.3.1 Graphite Properties

This part of work is performed within three tasks. Details of progress and assessment of results are as follows.

Task 1 – Review / state of the art

Graphite has been used as a neutron moderator in a number of different reactors including the Advanced Gas-cooled Reactors (AGRs), Magnox Reactors, High Temperature Reactors (HTRs), RBMKs, Research Reactors and Materials Testing Reactors (MTRs). However the amount of nuclear grade graphite currently manufactured worldwide is relatively small, and mainly consists of graphite for AGR fuel sleeves and prototype HTRs (one in Japan and one in China).

The graphite core is a key component that affects safety and operability of the reactor and validation of its through life performance is critically dependent on the knowledge of graphite properties which are affected by irradiation. One of the main functions of the graphite is to slow down fast neutrons, however when irradiated by fast neutrons graphite suffers crystalline damage, which results in a change in all physical and mechanical properties of the graphite. The most important property changes in this respect are strength, dimensional change (Fig. 5) and crystal coefficient of thermal expansion (CTE) (HTR-M 02/6-D-3.1.37). Changes to thermal conductivity are also large and dependent on the irradiation temperature. The other important consequence of the crystal damage is the build up of strain energy in the graphite components (referred to as Wigner energy or stored energy). However this is not a concern in graphite irradiated at high temperatures, as in the HTRs, but more relevant to graphite irradiated at low temperatures (i.e. Windscale Piles and some small research reactors).

The properties of graphite in a reactor environment have been extensively studied since the early 1940s and a good understanding of the significant and complex property changes that take place in the material has been gained. Most of the available data have been obtained by irradiating small graphite samples in MTRs. Unfortunately, almost all the graphites previously irradiated are no longer available. In addition, most of the irradiation temperatures investigated will have been <550^{o}C, whereas for HTRs the graphite temperatures will be >550^{o}C. The behaviour of currently available graphites will therefore have to be determined by experiments in a MTR over the appropriate irradiation dose and temperature range.

Task 2 - Database

Most of the available irradiated materials data are obtained from various materials test reactors and often it is not possible to complete an irradiated materials property database for a particular graphite in advance of design and construction phases of a reactor. In such cases design databases can be used to arrive at the required information, developed from previously irradiated graphites of similar microstuctures, and an understanding of irradiation damage in the polycrystalline graphites. R & D activities have been undertaken in a number of countries to investigate graphite properties. The IAEA International Irradiated Graphite Database Technical Steering provides a valuable forum for the exchange of information and opinion on graphites and has recently held seminars to review the current situation.

The work on review and collection of graphite properties (HTR-M 02/6-D-3.1.38) has considered the information within the IAEA database, internal information and published information at seminars and conferences. Two of the most significant experimental programmes in the past were for the European Dragon HTR programme, and the German HTR programme. Unfortunately most of the data obtained by other countries are confidential and so far are not published in open literature. However, data from the German HTR programme have been made available for publication and for the project. These data are being collated onto spreadsheets in a set format for use within the project and as for the steels will be considered for insertion into the JRC alloys-DB for housing the information on the web. It is proposed that the data is to be presented in the form of recommended 'design curves' for each required material property.

Task 3 Graphite selection

The final choice of graphite for the core should be based on a number of factors, although the most important will be the effects of fast neutron irradiation on its properties up to the peak doses envisaged. Given the best graphite available, it is the task of the core designer to produce a design that will operate safely over the design life of the reactor. The most important considerations are component integrity and changes in core geometry, both of which are affected by the dimensional change (HTR-M 02/11-D-3.2.53).

Meetings and discussions have been held with graphite manufactures and there has been much interest in providing materials for the test programme. Suitable graphites have been made available by UCAR and SGL who have offered extruded and iso-moulded graphites for the irradiation experiment. There has also been interest from other graphite manufacturers to supply material for the experiment and JAERI have offered international collaboration through Toyo Tanso who have proposed to supply the graphites they use in the HTTR reactor. It is clear that further input to graphite selection will be strongly influenced by the outcome of the planned irradiation experiment discussed under item 3.3.3 below.

3.3.2 Graphite Oxidation

The work on graphite oxidation involves tests in the THERA and INDEX facilities at FZJ. The work is largely complete and results in air and steam are available. Measurements have been taken on the kinetics of a German A3 fuel matrix graphite (type A3-27) and for a typical structural graphite (V483T fine grain graphite) for temperatures between 550 and 750^{o}C and partial pressures of between 2 and 20kPa in air and between 900 – 980°C at P[H2O] =1 in steam. The work also includes measurement of oxidation resistance and burn-ff (Fig. 6) of selected Carbon-Fibre-Composites (CFCs) developed for the Fusion Reactor. Experiments have also been carried out to determine the thermal conductivity of CFC materials in irradiated and non-irradiated samples.

From the results of the work (HTR-M 02/12 D 3.3.55 & HTR-M 02/12 D.3.3 56) the following conclusions have been made.

- The samples show roughly the same oxidation vs. burn-off behaviour in steam at both temperatures.
- With increasing burn-off the reaction rates in steam decrease.
- The carbon oxidation mechanisms of different materials are in detail different in air and in steam.
- The exact shape of rate vs. burn-off curves is different in both gases.
- A rate maximum for the CFCs, which was found in air, is not seen in steam.
- The steam rates at 1173 K correspond to those in air at 873 – 923 K.
- The activation energies in steam are higher than those in air.
- Despite its Si-content, the oxidation resistance of NS31 is not remarkably better than that of other examined materials (but a factor of 2 better than the CFC without Si).

Work during the remaining period of the programme will focus on introduction of the data into the database and clarification on the implications of the work with respect to future HTR requirements for air ingress events.

3.3.3 Graphite Irradiation

Following on from the review and selection of available graphites in HTR-M above the offered graphites for the experiment were agreed within HTR-M1 following the visits to the manufacturers.

UCAR:	Extruded petroleum coke	PCEA
	Iso-moulded petroleum coke	PCIB-SFG
SGL:	Extruded pitch coke	P3XA2N
	Iso-moulded petroleum coke	FNUY011
TOYO TANSO	Iso-moulded petroleum coke	IG-110

For these materials it is important also that the levels of impurities in the graphites are known in view of operational and waste issues (i.e. Boron, Cobalt, etc.).

If space is available both UCAR and SGL can offer “piggy back” grades, i.e. additional few numbers of samples for insertion where space is available, (UCAR an extruded pitch coke graphite & SGL an extruded petroleum coke graphite), although these “piggy back” positions cannot be guaranteed at this stage.

Characterisation of the graphites will be done at the facilities at NRG. These are to cover dimensional change, CTE (coefficient of thermal expansion), dynamic Young’s modulus and thermal diffusivity. For the CTE a commercial dilatometer is to be used.

The irradiation experiment will use a test rig that allows two distinct temperature levels to be obtained. Measurements will be on dimensional changes, Young’s modulus, CTE and thermal conductivity. The current programme must use currently available graphites since the development of a new material would take 3-5 years. Ideally the test conditions for the experiment would be those that give data for candidate graphites up the peak end of life fluence. This requires a significant effort over a long time scale, typically 10 years. The target flux in the current four year programme will be as high as possible. The proposal is to obtain a number of data points by using the flux (buckling) distribution available in the HFR capsule. A third order polynomial can describe the behaviour. The rig takes 3 sample stacks and the dimensions of the test pieces chosen according to grain size and to maximise the number of specimens for the tests.

4. List of Deliverables

A list of deliverables identified in the HTR-M & M1 contracts is given in Table 1.

The documents issued to date under the HTR-M and HTR-M1 projects are given in Table 2.

4.1 HTR-M Project

Commencement of work was 1st November 2000.

The project Kick-off meeting was held on 21st & 22nd November 2000 at NNC Ltd., Knutsford, UK. Minutes of the meeting have been issued (Ref. 1) and are available on the SINTER web site.

The first progress meeting was held on 18th & 19th April 2001 at NRG, Petten, Netherlands. Minutes of the meeting have been issued and are available on the SINTER web site (Ref. 2).

The second progress meeting, which included the kick-off meeting for the HTR-M1 project was held on 18th & 19th December 2001 at CEA, Grenoble, France. Minutes of this meeting have been issued and are available on the SINTER web site (Ref. 3).

A third meeting covering the joint progress of the HTR-M & HTR-M1 projects was held on 15th to 17th April, 2002 at FZJ, Jülich, Germany. Minutes of this meeting are available on the SINTER web site (Ref. 4).

The fourth meeting is to take place on 28th & 29th November at Framatome ANP, France.

Five technical papers have been prepared and presented at International Conferences (Ref. 5 to 9) including a recent paper for the ENC2002 conference held at Lille. These papers provide an overview of the HTR-M & M1 projects and a summary of the main areas of progress. A lecture on HTR materials dealing with aspects of metallic materials has been presented at the HTR Eurocourse at Cadarache.

Management reports on progress of the work performed over the first eighteen months of the project have been issued (Refs. 10 to 12) plus the first Annual Technical Report (Ref. 13).

Three deliverables are will be issued shortly for Work Package 1 on vessel steels on state of the art and review, database requirements and recommendations with respect to choice of material, defect assessment and LBB.

Six deliverables have been produced for Work Package 2 (Refs. 12-17) covering the design specifications, testing details, materials review and database for the Internals and Turbine. Deliverable 2.3 dealing with test details for the control rod material was delayed pending discussions and procurement of C/C composite material from potential suppliers for the test programme. The issue of the document should be completed by the end of the year following discussion of progress of the procurement and requirements for testing for C/C composite material at the November 2002 mid-term meeting.

Two deliverables have been produced for Work Package 3 (Refs.19 and 20) on graphite that provide a review and an outline of database requirements. A further deliverable dealing with graphite selection is to be issued shortly. Two reports detailing the results from test work on graphite corrosion are currently being written up. These provide chemical kinetic data for advanced oxidation models and results on oxidation resistance of advanced C based materials. A mid term report summarising the main conclusions from the HTR-M graphite work is also to be issued.

These documents provide our current understanding and will be updated as the project progresses.

4.2 HTR-M1 Project

Commencement of work was 1st October 2001.

The HTR-M1 project Kick-off meeting was held on 21st & 22nd December 2001 at CEA, Grenoble, France. Minutes of the meeting have been issued (Ref. 3) and are available on the SINTER web site.

A second meeting to review progress was held on 15th to 17th April, 2002 at FZJ, Julich, Germany. Minutes of the meeting are available on the SINTER web site (Ref. 4).

Three technical meetings have been held to review the requirements of the graphite irradiation programme of Work Package 2 and to discuss the availability and selection of the graphites to be included in the test programme. The minutes of these meeting are available on SINTER (Refs. 21 to 23).

Two technical deliverables have been issued, one on each Work Package, dealing with material selection and testing requirements.

5. Dissemination and Use of the Results

Dissemination and use of the results is being supported and guided by the co-ordination project HTR-C. This has responsibility for ensuring that all the HTR projects underway in the 5th Framework Programme act in a co-ordinated way. The other HTR projects underway in the 5th Framework Programme are HTR-F &F1, HTR-N & N1, HTR-E and HTR-L. They cover issues on Fuel, Nuclear Physics, Equipment, and Licensing. Through HTR-C key results from individual projects are discussed by the co-ordinators and information transferred through to benefit the other projects and to ensure a consistent technological development is maintained. Information has been exchanged between HTR-E at Work Package and PMT level on the turbine, use of cobalt in Ni based alloys, tribological issues and effects of environment, with HTR-N on graphite waste issues, with HTR-F on graphite properties and the possibility of using a higher flux position for graphite testing.

A wider European platform for dissemination and use of the results has been provided through the establishment of the HTR-Technology Network (HTR-TN). This network helps to direct progress towards solving key technological elements that have a strong influence on feasibility and future deployment of HTR technology within Europe. Through HTR-TN specific links on an International scale have been set up to promote a wider dissemination and exchange of information. This includes links with INET (China) and JAERI (Japan) as well as less formal interactions with current Industrial projects PBMR (South Africa) and GT-MHR for which a number of HTR-TN and HTR Project partners are already active. Close collaboration of European organisations with the test reactors HTR-10 and HTTR is considered to be a necessary pre-condition for any future involvement in HTR projects outside Europe.

5.1 Functional Analysis of the main deliverables

5.1.1 Vessel materials

The review work and database work has identified the available information and data to be incorporated and confirmed the choice of modified 9Cr 1Mo steel as the material to use in the irradiation test programme. Properties for inclusion in the database are to be assembled to provide a platform of materials information for technological development. A recommendation has been made that thermal ageing should be investigated in the future.

The fabrication difficulties experienced in manufacturing the thick section welded features confirmed the need for the R & D work carried out within HTR-M. More work is still needed to overcome the cracking found in the welds and to validate modified 9Cr 1Mo steel as a vessel material.

5.1.2. High temperature materials

The review work has identified a short list of materials and available properties for inclusion in the database together with published information on experiences on manufacture and effects of environment. Properties for inclusion in the database are to be assembled to provide a platform of materials information for technological development of the turbine and control rod. Irradiated properties will ultimately be required for C/C composite materials. Most published information is from Fusion applications and a wider dissemination to and from this area should prove beneficial. No published information is available on effect of irradiation on turbine blade and disc alloys. This information will be needed for performance and decommissioning assessment by turbine suppliers and reactor operators in the longer term.

5.1.3. Graphite

The need for reliable graphite data is a crucial issue for existing and new HTR projects. Graphite performance in the reactor has important safety implications because of structural and other property changes that occur when it is irradiated. Its selection also has significant consequences for future decommissioning activities. Oxidation resistance of graphites at high temperature requires special attention due to its relevance for safety analyses of air and water ingress accidents, licensing procedure and normal operation.

Most graphites that have been used in previous core designs are no longer manufactured commercially, and currently available grades are limited to a few specific sources of raw materials. Few may turn out to be suitable or desirable for a European based modular HTR. Recognising this and the need for information for design and feasibility assessment, cooperation with graphite manufacturers began at the outset of HTR-M1 to encourage open exchange of information on all issues affecting material availability and behaviour. It is hoped that this strategy will lead to the rapid selection of suitable graphites in the short term and the development of an improved graphite in the longer term as well as establishing a close relationship between user and supplier for future HTR development.

Although the current project falls short of the ultimate selection criteria for the graphite, which will mainly be based on long-term irradiation behaviour, it does provide the groundwork for continuation of the irradiation programme on the most desirable graphite(s) and makes use of the valuable diminishing experience from experts in design, experiments and testing of graphite within Europe serving to reinstall graphite irradiation and qualification methods within Europe while the available experience and facilities exists.

5.2 Value analysis study

The benefits of the HTR-M work are considered to have a significant impact on the future development of HTR Technology development in Europe. Material knowledge is considered to be a basic requirement and the starting point to many feasibility and research orientated activities. The materials information being acquired through HTR-M & M1 are fundamental to the HTR development. They are important to the validation of the containment provided by the vessel, the operability of the turbine and control rod and the functionality of the core.

- Suitability of modified 9Cr 1Mo steel for “warm” HTR vessel application. Measurement of irradiation data and evaluation of the fabrication potential for HTR vessel application.

- Selection of best available turbine disc and blade materials for HTR application. Measurement of properties and strength under HTR relevant conditions.

- Investigation of C/C as a future material for control rod.

- First selection of possible graphites for the HTR. Irradiation of these new graphites to assess their suitability.

- Oxidation potential of graphite in an air ingress situation. Comparative evaluation of available composites.

At this stage it is difficult to perform a real value analysis of the technical information given that many of the experimental programmes have not yet started. However it is expected that relative value of all the activities will be high.

The potential benefit of the HTR technology deployment as a whole is considered to be significant in terms of sustainable employment and “return of investment”. Also in recovering past knowledge and know-how (more than 5 billion EUR have already been spent on HTR development in the past). It is important to recover as much of this information as possible through development and deployment of those skills if Europe is to make a significant contribution alongside other forums and international initiatives.

5.3 Protection of results

The current agreement within the partnership of HTR-M & M1 drawn up at the contractual stage of the projects are as follows:

Background information:

Each partner may disclose to other participants, on a royalty-free basis, his background information for the implementation of the European Project for the Development of HTR Technology. Each partner shall remain the owner of his own background information. If such background information is needed by another partners for any other use than the implementation of the European Project, they should request permission from the owner of the background information on conditions to be mutually agreed upon.

Foreground information:

The foreground information generated shall be disclosed to all the participants of the European Project for the Development of HTR Technology. Disclosure of the foreground information to parties outside the European Project will be possible only subject to agreement. Each partner or group of partners generating an invention from this work may file a patent or take any measure to protect his invention. For any use of an invention other than the implementation of the European Project, the inventor on conditions to be mutually agreed upon could be granted a license.

The results of the project are archived in an electronic form on the SINTER Network Internet Site. The access is restricted to partners and collaborative organisations and monitored by the co-ordinator.

5.4 Targeted audience / recipients for dissemination / transfer of information

The partnership within HTR-M & M1 have agreed to disseminate the findings from their results through to other projects via the HTR-C co-ordination. They have also agreed to disseminate findings on a more general level and to a wider audience through the HTR Technology Network HTR-TN. The targeted audiences to date are as follows.

- The partnership and invited observers to the HTR-M & M1 project meetings.
- The partnerships within the current projects HTR-F &F1, HTR-N &N1, HTR-E, HTR-L via the HTR-C coordination.
- Collaboration with relevant ISTC projects.
- The European HTR-TN network which includes over 20 partner organisations consisting of manufacturers, R & D organisations , industrial organisations and users.
- International conferences & Eurocourse activities.
- International co-operation with China, Japan, USA and South Africa through regulated exchanges via the HTR-TN network.

- Through regulated exchanges connected with the Generation IV Forum (GIF).

6. Management and Co-ordination Aspects

Overall the progress of the work is considered to be satisfactory and largely to programme.

Co-ordination continues to be achieved through the main progress meetings. Separate technical meetings in between the main co-ordination meetings have taken place where needed. These have been mainly on graphite material issues, material procurement and test requirements for the turbine materials.

Co-ordination and managing of the vessels work is being done by NRG who are responsible for the irradiation tests in HFR. CEA is co-ordinating the high temperature materials and CEA and JRC are responsible for performing the tests on the turbine disc and blade materials CEA will perform the tests on C/C composites for the control rod. The graphite materials work is being co-ordinated by NNC working in close consultation with NRG and FZJ who are also responsible for the oxidation and irradiation tests.

A detailed programme of the Work Packages is available on SINTER and will be updated by Work Package leaders throughout the project as an aid to project planning and development. An overall description of the programme is given in figure 7.

Analysis of the information (table 4) on resource and manpower allocation shows that the HTR-M project is approximately 60% complete and the HTR-M1 project approximately 30% complete. This is consistent with the overall planning and the targets achieved.

Duplication of effort within the review work has been minimised by suitable work sharing between participating partners. A significant number of documents and reports have been produced and all the required deliverables completed. Much of the recent effort has been placed on material procurement and selection in order to begin the machining and characterisation of the test specimens as early as possible for the test programmes. This has involved contact / discussions with specialist materials suppliers. The planning for the irradiation experiments is well advanced and the test pieces are expected to meet the reloading schedule of the HFR.

7. Conclusions

The objective of the HTR-M project is to improve knowledge of materials for future HTRs for the reactor pressure vessel, the control rod and turbine (blades & discs) and the reactor graphite. The scientific and technical progress for the HTR-M project has been described and issues that are likely to influence the technical decisions on the next stage of the programme reviewed. The review work has largely been completed in all three areas and the database work ready to progress to the information retrieval activity to take place throughout the remainder of the project.

The vessel review work has concentrated on materials used in new and developing plants and has identified modified 9Cr 1Mo steel, which has the wider applicability and most uncertainties on database and fabrication experience (with respect to HTR vessel characteristics), as the steel for the irradiation tests. The fabrication of weld sections for extraction of test pieces has met with some difficulty however machining and characterisation of test pieces is expected to be completed for HFR availability.

The review and database activity show C/C composite materials as a possible alternative to metals for the control rod. For the turbine (disc and blades) a review and short list of alloys has been produced and candidate alloys selected for the test programme. Procurement of material is underway to allow short-term experiments to start in 2003. Intermediate creep testing of material is planned to start as soon as possible in 2003 under the HTR-M1 project.

The work on the graphite has identified a few candidates for the irradiation test programme and these are currently being machined and characterised at NRG. The test work on graphite oxidation is largely complete. Introduction of the test information onto the database and clarification on the implications of the work with respect to future HTR requirements for air ingress events will continue.

Overall the project is progressing to programme. There have been some delays in the procurement/ fabrication of material for the test programmes but these have not had a significant effect on the overall project time schedule. The next few months will see the continuation of machining and characterisation of test specimens for the tests programmes and the commencement of the experiments as soon as the test facilities / specimens are available. The irradiation of the vessel steel and the graphite test pieces in the HFR are expected to begin in 2003 following characterisation of the test pieces by NRG.

8. References

Ref	Title
1	K. Peers. European Project for the development of HTR Technology Minutes of HTR-M Kick-off Meeting Report No. HTR-M-01/3-M-0-0-4
2	R.D. Bestwick European Project for the development of HTR Technology Minutes of HTR-M Progress Meeting Report No. HTR-M-01/5-M-0-0-5
3	D. E. Buckthorpe European Project for the development of HTR Technology Minutes of HTR-M1 Kick-off plus 2nd HTR-M progress meeting Report No. HTR-M-01/11-M-0-0-26
4	D. E. Buckthorpe European Project for the development of HTR Technology Minutes of HTR-M plus HTR-M1 Progress Meeting Report No. HTR-M-02/5-M-0-0-33
5	D.E. Buckthorpe, et. al. Materials for the High Temperature Reactor 16th SMiRT Conference, Washington, USA, on 12-17th August 2001 Report No. HTR-M-01/5-D-0-0-6
6	D.E. Buckthorpe, et. al. Investigation of the High Temperature Reactor (HTR) Materials NEA/OECD, 2nd Information Exchange meeting on High Temperature Engineering, Paris, on 10-12 October 2001 Report No. HTR-M-01/10-D-0-0-16
7	D.E. Buckthorpe, et. al. Materials for the High Temperature Reactor HTR2002 Conference, Petten, Netherlands, on 21-23 April 2002 Report No. HTR-M-02/3-D-0-0-29
8	D.E. Buckthorpe, et. al. High Temperature Reactor (HTR) Materials Poster paper for the 7th Liege Conference on materials, Liege, Belgium, on 30th September – 2nd October 2002 Report No. HTR-M-02/3-D-0-0-30
9	D.E. Buckthorpe, et. al. European project on Materials for modular HTRs ENC2002 Conference, Lille, France, on 7- 9th October 2002 Report No. HTR-M-02/9-D-0-0-46
10	D.E. Buckthorpe, et. al. Six month management report for the HTR-M project Report No. HTR-M-01/5-P-0-0-8

Ref	Title
11	D.E. Buckthorpe, et. al. Twelve month management report for the HTR-M project Report No. HTR-M-01/11-P-0-0-25
12	D.E. Buckthorpe, et. al. Eighteen month management report for the HTR-M project Report No. HTR-M-02/5-P-0-0-34
13	D.E. Buckthorpe, et. al. First Annual Technical Report for the HTR-M project Report No. HTR-M-01/11-D-0-0-24
14	B. Riou HTR-M Specification for Internals Report No. HTR-M-01/7-D-2-1-14
15	B Riou HTR-M Specification for Turbine Report No. HTR-M-01/9-D-2-1-19
16	R. Couturier Materials for Turbine: Definition of Complementary Testing Experiments Report No. HTR-M 02/6-D-2-2-35
17	D.E. Buckthorpe & C.J. Earl Materials for the Core and Internals: Synthesis of Materials Database Report No. HTR-M 02/6-D-2-1-36
18	D.E. Buckthorpe & C.J. Earl Materials for turbine: Synthesis of Materials Database Report No. HTR-M 02/6-D-2-1-39
19	M. Davies & G. Haag State of Art review of graphite materials behaviour Report No. HTR-M 02/6-D-3-1-37
20	M. Davies Report on database of properties suitable for use by designer Report No. HTR-M 02/6-D-3-1-38
21	J. Van der Laan Minutes of 1st Technical meeting on graphite held on 13th Nov. 2001 at NRG Petten, Netherlands Report No. HTR-M1-02/1-M-2-0-1

Ref	Title
22	M. W. Davies Minutes of meeting with graphite manufacturer UCAR on 26$^{th.}$ March 2002, Notre Dame, France Report No. HTR-M1-02/1-M-2-0-3
23	M. W. Davies Minutes of meeting with graphite manufacturer SGL on 27th March 2002, Chedde, France Report No. HTR-M1-02/1-M-2-0-4
24	D. E. Buckthorpe Notes of Meeting with JAERI on 24th April 2002, Petten, Netherlands Report No. HTR-TN(02)-TG6-M-006
25	D. E. Buckthorpe Notes of Meeting with US NRC & D.O.E on 24th April 2002, Petten, Netherlands Report No. HTR-TN(02)-TG6-M-004
26	D. E. Buckthorpe Notes of Meeting with US NRC on 25th April 2002, Petten, Netherlands Report No. HTR-TN(02)-TG6-M-005
27	M. Hugon Notes of Meeting of ISTC Contact expert group on GT – MHR on 25th April 2002, Petten, Netherlands Report No. HTR-TN(02)-TG6-M-007

Table 1. HTR-M Deliverables list (WP1)

Deliverable No	Deliverable title	Delivery date	Current planned	Date Achieved	Main Organisation
1.1	Database on pressure vessel steel plate and weld material for reactor pressure vessel (RPV)	24	01/11/2002	24	NNC
1.2	State of the art on HTR vessel materials	24	01/11/2002	25	NNC
1.3	Recommendations for RPV design, choice of material, defect assessment and leak before break methodology	24	01/11/2002	25	CEA /EA
1.4	Evaluation of factors for defect tolerance of RPV weld	42	01/05/2004	-	FRA
1.5	Complementary irradiation data on base material and weld	42	01/05/2004	-	NRG
1.6	Summary report on vessel materials	48	01/11/2004	-	NRG

Table 1. HTR-M Deliverables list (WP2)

Deliverable No	Deliverable title	Delivery date	Current planned	Date Achieved	Main Organisation
2.1	***Materials for core and internals*** : Report on design specifications and operating conditions by partner 2	9	01/07/2001	9	FRA
2.2	***Materials for core and internals***: Synthesis of materials database	18	01/05/2002	19	NNC
2.3	***Materials for core and internals***: Definition of complementary testing experiments	18	01/05/2002	Delayed	CEA/JRC
2.4	***Materials for core and internals***: Report on preliminary material testing	36	01/11/2003	-	CEA/JRC
2.5	***Materials for core and internals***: Final report on material grade and processing, synthesis of further R&D efforts needed.	48	01/11/2004	-	CEA
2.6	***Materials for turbine*** : Report on design specifications and operating conditions	9	01/07/2001	11	FRA
2.7	***Materials for turbine*** : Synthesis of materials database	18	01/05/2002	19	NNC
2.8	***Materials for turbine*** : Definition of complementary testing experiments	18	01/05/2002	19	CEA/JRC
2.9	***Materials for turbine*** : Report on preliminary material testing and progress on material cyclic tests	36	01/11/2003	-	CEA/JRC
2.10	***Materials for turbine***: Final report on material grade and processing and material tests, synthesis of further R&D efforts needed.	48	01/11/2004	-	CEA

Table 1. HTR-M Deliverables list (WP3)

Deliverable No	Deliverable title	Delivery date	Current planned	Date Achieved	Main Organisation
3.1	State of the art review of graphite materials and behaviour	18	01/05/2002	19	NNC/FZJ
3.2	Report on database of properties of graphite suitable for use by the designer	18	01/05/2002	19	NNC
3.3	Assess new potential graphites and needs of HTR	24	01/11/2002	25	NNC/FZJ
3.4	Report on chemical kinetic data for advanced oxidation models	24	01/11/2002	25	FZJ
3.5	Report on oxidation resistance of advanced C-based materials	24	01/11/2002	25	FZJ
3.6	Final Report Summary	24	01/11/2002	25	NNC

Table 1. HTR-M1 Deliverables list (WP1)

Deliverable No	Deliverable title	Delivery date	Current planned	Date Achieved	Main Organisation
D1	Report on selection of materials & testing requirements	12	01/10/2002	11	CEA
D2	Report on specimen fabrication and procurement & testing requirements	18	01/04/2003	-	CEA
D3	Report on material testing	42	01/04/2005	-	CEA
D4	Damage analysis and modelling	42	01/04/2005	-	CEA
D5	Review of results and updating of database	42	01/04/2005	-	CEA
D6	Final Report summary	42	01/04/2005	-	FRA

Table 1. HTR-M1 Deliverables list (WP2)

Deliverable No	Deliverable title	Delivery date	Current planned	Date Achieved	Main Organisation
D7	Report on selection of graphites and testing requirements	12	01/10/2002	14	NNC
D8	Report on specimen fabrication and procurement	18	01/04/2003	-	NRG
D9	Report on irradiation and post irradiation tests	42	01/04/2005	-	NRG
D10	Review of results and updating of database	42	01/04/2005	-	NRG
D11	Assessment of results and suitability	42	01/04/2005	-	FZJ
D12	Final Report Summary	42	01/04/2005	-	NNC

Table 2 HTR-M Project document list

HTR No..	Status	Final issue date	Title	Author / Org
HTR-M-01/3-D-0-0-1	Final	March 2001	HTR-M Release Data	T.Austin / JRC
HTR-M-01/3-D-0-0-2	Draft		On-line Alloys-DB Access Agreement	T. Austin / JRC
HTR-M-01/3-D-0-0-3	Draft		Technological Implementation Plan	D. Buckthorpe / NNC
HTR-M-01/3-M-0-0-4	Final	April 2001	Minutes of HTR-M Kick-off Meeting, held on 21/22 November 2000 at NNC Ltd., UK	K.Peers / NNC
HTR-M-01/5-M-0-0-5	Final	Dec 2001	Minutes of HTR-M First Progress Meeting held on 18/19 April 2001 at NRG, Petten, Netherlands	R.D.W.Bestwick / NNC
HTR-M-01/5-D-0-0-6	Final	May 2001	Materials for the High Temperature Reactor, SMiRT 16 paper No. 1941, Div S. Washington, U.S.A, Aug. 2001	D. Buckthorpe / NNC et. al.
HTR-M-01/5-P-0-0-7	Final	July 2001	HTR-M Six Month Management Report	D. Buckthorpe / NNC
HTR-M-01/5-D-0-0-8	Final	July 2001	Summary of technical work done over first Six Months of HTR-M	D. Buckthorpe / NNC et. al.
HTR-M-01/9-D-1-1-9	Draft		HTR-M project - Preliminary review of RPV materials used on HTR and other gas reactors	R.D.W.Bestwick / NNC
HTR-M-01/9-D-2-0-10	Draft		HTR-M Work Package 2 - Detailed description of tasks	R. Couturier / CEA
HTR-M-01/9-D-2-1-11	Final	Inserted Sept. 2001	Development of carbon/ carbon composite control rod for HTTR (II) - Concept, specification and mechanical test of materials	JAERI Research 98-003/ Japan
HTR-M-01/9-M-2-0-12	Draft		HTR-M Work Package 2, Milestone 2 Materials review and database	R. Couturier / CEA
HTR-M-01/9-M-2-0-13	Draft		Bibliography of papers for HTR-M Work Package 2	R. Couturier / CEA
HTR-M-01/7-D-2-1-14	Draft		HTR-M Design use and Specification for Internals	B. Riou / Framatome
HTR-M-01/7-D-1-0-15	Draft		HTR-M Work Package 1 - Detailed description of tasks	H. Hegeman & B van der Schaaf / NRG
HTR-M-01/10-D-0-0-16	Final	Oct. 2001	Investigation of High Temperature Reactor (HTR) Materials, OECD paper, 2nd Information exchange meeting of High Temperature Engineering, Paris, 11-12 Oct 2001	D. Buckthorpe / NNC et. al.

Table 2 (cont)	**HTR-M Project document list**

HTR No..	Status	Final issue date	Title	Author / Org
HTR-M -01/10-D-1-1-17	Draft		Material selection for HTR Pressure Vessel	A. Buenaventura EA
HTR-M 01/11 D.1.1.18	Draft		Report on Damage Mechanisms	M.T.Cabrillat CEA
HTR-M 01/10 D-2-1-19	Draft		HTR-M Design use and Specification for Turbine	B. Riou / Framatome
HTR-M 01/10 D-3-0-20	Draft		HTR-M Work Package 3 - Description of Tasks	D. Buckthorpe / NNC
HTR-M 01/3 D.0.0.21	Draft		HTR-M Materials Database - scope and proposed stages of development	D. Buckthope NNC
HTR-M 01/11 D.0.0.22	Draft		Scheme for HTR-M Materials data collection	D. Buckthorpe NNC
HTR-M 01/3 D.2.0.23	Draft		Information needs on "Turbine design and operating conditions" for the choice of high temperature materials and experimental test conditions	R. Couturier CEA
HTR-M 01/11 P-0-0-24	Final	Dec 2001	HTR-M First Annual Report	D. Buckthorpe / NNC
HTR-M 01/11 P-0-0-25	Final	Dec 2001	HTR-M Twelve month management report	D. Buckthorpe / NNC
HTR-M 02/01 M.0.0.26	Final	April 2002	Minutes of the HTR-M1 Kick-off plus 2nd HTR-M Progress Meeting on 5-7 December 2001, Grenoble, France	D. E. Buckthorpe / NNC
HTR-M 02/02 D.1.1.27	Draft		HTR RPV Materials Damage Mechanisms	A. Buenaventura EA
HTR-M 02/02 D.1.1.28	Draft		HTR RPV Sensitive Zones	A. Buenaventura EA
HTR-M 02/03 D.0.0.29	Final	April 2002	Materials for the High Temperature Reactor, HTR2002 Conference, Petten, 22-24th April 2002 (poster paper)	D. E. Buckthorpe /NNC Et.al.
HTR-M 02/03 D.0.0.30	Final	Oct 2002	High Temperature Reactor (HTR) Materials, Liege Conference, 30th Sept. to 2nd Oct., 2002 (poster paper)	D. E. Buckthorpe / NNC Et.al.
HTR-M 02/04 D 1.1.31	Draft		HTR - Identification and review of pressure vessel candidate materials	C. Escaravage / Framatome-ANP
HTR-M 02/04 D 2.2.32	Draft		HTR: Identification and review of turbine candidate materials	C. Escaravage / Framatome-ANP
HTR-M 02/5 M 0.0.33	Final	Nov 2002	Minutes of the HTR-M & M1 Progress Meeting on 15-17 April; 2002, Julich, Germany	D. E. Buckthorpe NNC Ltd.
HTR-M-02/5-P-0-0-34	Final	July 2002	18 month HTR-M plus 6 month HTR-M1 joint management report	D. E. Buckthorpe NNC Ltd.
HTR-M 02/6 D 2 2 35	Draft		Materials for Turbine: Definition of Complementary testing experiments	R. Couturier / CEA

Table 2 (cont) HTR-M Project document list

HTR No.	Status	Final issue date	Title	Author / Org
HTR-M 02/6 D 2 1 36	Draft		Materials for the Core and Internals: Synthesis of Materials Database	D. E. Buckthorpe & C. J. Earl/ NNC
HTR-M 02/6 D 3 1 37	Draft		State of Art review of graphite materials behaviour	M.W. Davies / NNC G Haag / FZJ
HTR-M 02/6 D 3 1 38	Draft		Report on database of properties suitable for use by designer	M.W. Davies / NNC
HTR-M 02/7 D 2 1 39	Draft		Materials for turbine: synthesis of materials database	D.E.Buckthorpe & C.J.Earl/ NNC
HTR-M 02/8 D 1 1 40	Draft		Recommendations for RPV design, choice of material, defect assessment and leak before break methodology	M.T.Cabrillat / CEA A. Buenaventura / EA
HTR-M 02/9 D 1 1 41	Draft		HTR Compared properties of Pressure Vessel candidate materials	C. Escaravage / Framatome ANP
HTR-M 02/10 D 0 0 42	Final	Oct. 2002	Design Criteria for High Temperature Metallic and Ceramic Components as well as Pre-Stressed Concrete Reactor Pressure Vessels for Future HTR Plants - Volume I, Part A: Safety technological boundary conditions.	(In German) Provided for the Project by FZJ
HTR-M 02/10 D 0 0 43	Final	Oct. 2002	Design Criteria for High Temperature Metallic and Ceramic Components as well as Pre-Stressed Concrete Reactor Pressure Vessels for Future HTR Plants - Volume IIa, Part B: Metallic Components.(B1, B2, B10)	(In German) Provided for the Project by FZJ
HTR-M 02/10 D 0 0 44	Final	Oct. 2002	Design Criteria for High Temperature Metallic and Ceramic Components as well as Pre-Stressed Concrete Reactor Pressure Vessels for Future HTR Plants - Volume IIb, Part B: Metallic Components.(B3 to B9)	(In German) Provided for the Project by FZJ
HTR-M 02/10 D 0 0 45	Final	Oct. 2002	Design Criteria for High Temperature Metallic and Ceramic Components as well as Pre-Stressed Concrete Reactor Pressure Vessels for Future HTR Plants – Volume IV, Part D: Graphite Reactor Internals.	(In German) Provided for the Project by FZJ

Table 2 (cont) HTR-M Project document list

HTR No..	Status	Final issue date	Title	Author / Org
HTR-M 02/10 D 0.0 46	Final	Oct 2002	European Project on Materials for Modular HTRs, ENC2002 Conference, Lille, France, 7-9th Oct., 2002	D. E. Buckthorpe / NNC Et.al.
HTR-M 02/11 P 0.0 47	Draft		Mid-term report for the HTR-M & M1 Projects	D. E. Buckthorpe NNC Ltd
HTR-M 02/11 D 1 1 48	Draft		Review of irradiation and thermal ageing - effects in modified 9Cr 1Mo steel	A. Braithwaite / NNC Ltd.
HTR-M 02/11 D 1 1 49	Draft		State of the art review of HTR materials	R.D.W.Bestwick / NNC Ltd.
HTR-M 02/11 D 0 0 50	Draft		The HTR-M vessel materials database	A. Braithwaite / NNC Ltd
HTR-M 02/11 D 0 0 51	Draft		HTR-M vessel materials database Nov 02	A. Braithwaite / NNC Ltd
HTR-M 02/11 D 2 0 52	Draft		WP6 Review of the gas / Ni based alloy interactions in HTR impure Helium	P. Combrade / Framatome.ANP SAS
HTR-M 02/11 D 3 2 53	Draft		Assess new potential graphites and needs of HTR	M. W. Davies/ NNC Ltd.
HTR-M 02/12 D 2 0 54	Draft		HTR-E Work Package 1 Turbine – HTR recommendations of cobalt content in turbine materials	C. Mauget / Framatome.ANP
HTR-M 02/12 D 3 3 55	Draft		Oxidation resistance of Carbon based materials	K. Kuhn, H-K Hinssen, R. Moormann / FZJ
HTR-M 02/12 D 3 3 56	Draft		Chemical kinetic data for advanced oxidation models	K. Kuhn, H-K Hinssen, R. Moormann / FZJ
HTR-M 02/12 P 0 0 57	Draft		24 Month HTR-M plus 12 month HTR-M1 Management Report	D. E. Buckthorpe NNC Ltd
HTR-M 02/12 D 3 0 58	Draft		Summary report – work performed on graphite within the HTR-M project	D. E. Buckthorpe NNC Ltd
HTR-M 02/12 P 0 0 59	Draft		24 Month HTR-M plus 12 month HTR-M1 Management Report	D. E. Buckthorpe NNC Ltd

Table 2 (cont)	HTR-M1 Project document list

HTR No..	Status	Final issue date	Title	Author / Org
HTR-M1 02/1 M 2.0.1	Final	April 2002	Minutes of 1st Technical meeting on graphite held on 13th Nov. 2001 at NRG Petten, Netherlands	J. van der Laan/ NRG Petten
HTR-M1 02/1 M.0.0.2	Final	April 2002	Minutes of the HTR-M1 Kick-off plus 2nd HTR-M Progress Meeting on 5-7 December 2001, Grenoble	D.E. Buckthorpe/ NNC Ltd.
HTR-M1 02/5 M 2.0.3	Final	July 2002	Minutes of meeting with graphite manufacturer UCAR on 26th. March 2002, Notre Dame, France	M. W. Davies/ NNC Ltd
HTR-M1 02/5 M 2.0.4	Final	July 2002	Minutes of meeting with graphite manufacturer SGL on 27th March 2002, Chedde, France	M. W. Davies/ NNC Ltd
HTR-M1 02/5 M 0.0.5	Final	Nov 2002	Minutes of the HTR-M / M1 Progress Meeting on 15-17 April 2002, Julich, Germany	D.E. Buckthorpe/ NNC Ltd.
HTR-M1 02/5 P 0.0.6	Final	July 2002	18month HTR-M plus 6 month HTR-M1 joint management report	D. E. Buckthorpe NNC Ltd.
HTR-M1 02/9 D 1 1 7	Draft		HTR-M1: Report on selection of materials & testing requirements for the Turbine	R. Couturier / CEA
HTR-M1 02/11 P 0 0 8	Draft		Mid-term report for the HTR-M & M1 Projects	D. E. Buckthorpe NNC Ltd
HTR-M1 02/11 D 2 1 9	Draft		Report on selection of graphites and testing requirements	M. W. Davies/ NNC Ltd
HTR-M1 02/12 M 0 0 10	Draft		Minutes of the HTR-M plus M1 Mid Term Meeting on 28-29 November; 2002, Framatome, Paris	D. E. Buckthorpe NNC Ltd
HTR-M1 02/12 P 0 0 11	Draft		24 Month HTR-M plus 12 month HTR-M1 Management Report	D. E. Buckthorpe NNC Ltd

Table 3. HTR test reactors and designs for future plant

Country	Japan					South Africa	Russia + others	China	
System (1)	HTTR	MSF HTR	SSF HTR	HTR -GT 300	HTR -GT 600	PBMR	GT-MHR	HTR 10	MHGTR -IGT
Purpose (2)	Tests	H+E	E+DS	E	E	E	E	Tests	E+DS
Power, MW t	30	450-600	50	300	600	265	600	10	200
Core Type)	Block	Bloc	Block	P. Bed	Block	P. Bed	Block	P. Bed	P. Bed
He Pressure, MPa	4	6	7	6	6	7	8	3	6
Core inlet, °C	395	350 550	490	550	460	536	490	300 (8)	550
Core Outlet, °C	850 950	850 950	850	900	850	900	850	900 (8)	900
RPV wall, °C	400	-	-	<350	460	300	440	-	<350
RPV ID, m	5.5	-	-	7.27		6.2	7.3	2.5	6
Belt line thk., mm (3)(4)	122	-	-	150	-	140	200 approx.	100 approx.	-
Flange thk., mm (4)	300 approx	-	-	550 approx	-	365	670	-	-
Vessel mass, te (5)	-	-	-	800 (V)	<1000 (V)	600	1362 (V+C)	142	-
Material	2¼ Cr 1Mo	Mod 9Cr	Mod 9Cr	SA508	Mod 9Cr	SA508	Mod 9Cr	SA516 -70	-

Notes:

(1) Initials are as used in Refs. 1 and 2.

(2) E = electricity generation, H = hydrogen production, DS = de-salination

(3) BL = belt line, usually the minimum shell thickness. Max usually refers to that part of the cylinder containing the 'cross vessel' connection between the RPV and the power system vessel.

(4) Thickness is called 'approx.' when estimated from a small-scale drawing.

(5) V = vessel only - excluding bolted closure. V+C includes bolted closure, vessel mass about 1000 te.

Table 4 Analysis tables

HTR-M Budget Follow-up Table

PARTNER	Cost Category	Budget	ACTUAL COSTS					Total Pct. Spent (%)				Remaining Budget	Comments
			Year 1	Year 2	Year 3	Yeasr 4	Total	Year 1	Year 2	Year 3	Year 4		
	Personnel	206,511	62,344	56,672			119,016	30.2%	57.6%			87,495	
	Overhead	206511	96,011	87,277			183,288	46.5%	88.8%			23,223	
	Travel	12978	8,360	1,642			10,002	64.4%	77.1%			2,976	
	Durable Eqmt	0	0				0	-	-		-	0	
NNC	Consumables	0	0	0			0	-	-		-	0	
	Subcontracting	0	0				0	-	-		-	0	
	Computing	0	0				0	-	-		-	0	
	Other	0	0				0	-	-		-	0	
	total	**426,000**	**166,714**	**145,592**	***0***		**312,306**	***39.1%***	***73.3%***			113,694	
	Personnel	165,911	19,722	86,779			106,501	11.9%	64.2%			59,410	
	Overhead	147127	17,491	76,943			94,433	11.9%	64.2%			52,694	
	Travel	8340	1,986	1,479			3,465	23.8%	41.5%			4,875	
	Durable Eqmt	0	0				0	-	-		-	0	
Framatome.ANP	Consumables	7622	0				0	0.0%	0.0%			7,622	
	Subcontracting	0	0				0	-	-		-	0	
	Computing	0	0				0	-	-		-	0	
	Other	0	136				136	-	-		-	-136	
	total	**329,000**	**39,334**	**165,201**	***0***		**204,535**	***12.0%***	***62.2%***			124,465	
	Personnel	204,579	54,162	72,501			126,663	26.5%	61.9%			77,916	
	Overhead	221967	54,245	73,115			127,360	24.4%	57.4%			94,607	
	Travel	7454	2,177	1,530			3,707	29.2%	49.7%			3,747	
	Durable Eqmt	0	0	0			0	-	-		-	0	
CEA	Consumables	100000	6,639	28,326			34,965	6.6%	35.0%			65,035	
	Subcontracting	20000	0	2,951			2,951	0.0%	14.8%			17,049	
	Computing	0	0	0			0	-	-		-	0	
	Other	0	0	0			0	-	-		-	0	
	total	**554,000**	**117,224**	**178,423**	***0***		**295,647**	***21.2%***	***53.4%***			258,353	
	Personnel	87,645	8,293	13,087			21,380	9.5%	24.4%			66,265	
	Overhead	61355	6,865	10,892			17,757	11.2%	28.9%			43,598	
	Travel	8000	784	1,087			1,870	9.8%	23.4%			6,130	
	Durable Eqmt	0	0	0			0	-	-		-	0	
NRG	Consumables	60000	1,040	3,764			4,804	1.7%	8.0%			55,196	
	Subcontracting	0	0	0			0	-	-		-	0	
	Computing	0	0	0			0	-	-		-	0	
	Other	40000	0	0			0	0.0%	0.0%			40,000	
	total	**257,000**	**16,983**	***28,829***	***0***		**45,812**	***6.6%***	***17.8%***			211,188	
	Personnel	170,811	24,134	59,611			83,746	14.1%	49.0%			87,065	
	Overhead	45087	5,894	12,882			18,776	13.1%	41.6%			26,311	
	Travel	5071	2,030	4,335			6,365	40.0%	125.5%			-1,294	
	Durable Eqmt	10000	0	0			0	0.0%	0.0%			10,000	
JRC	Consumables	27031	0	0			0	0.0%	0.0%			27,031	
	Subcontracting	0	0	0			0	-	-		-	0	
	Computing	0	0	0			0	-	-		-	0	
	Other	0	0	0			0	-	-		-	0	
	total	**258,000**	**32,058**	**76,829**	***0***		**108,887**	***12.4%***	***42.2%***			149,113	
	Personnel	119,791	38,117	89,892			128,009	31.8%	106.9%			-8,218	
	Overhead	111089	37,072	69,274			106,346	33.4%	95.7%			4,743	
	Travel	10120	1,612	5,417			7,030	15.9%	69.5%			3,090	
	Durable Eqmt	0	0	0			0	-	-		-	0	
FZJ	Consumables	0	253				253	-	-		-	-253	Budget Spent
	Subcontracting	0	0				0	-	-		-	0	
	Computing	0	0				0	-	-		-	0	
	Other	0	0				0	-	-		-	0	
	total	**241,000**	**77,055**	**164,583**	***0***		**241,638**	***32.0%***	***100.3%***			-638	
	Personnel	27,904	4,393	8,990			13,383	15.7%	48.0%			14,521	
	Overhead	30289	4,768	9,761			14,529	15.7%	48.0%			15,760	
	Travel	6807	2,301	0			2,301	33.8%	33.8%			4,506	
	Durable Eqmt	0	0	0			0	-	-		-	0	
EA	Consumables	0	0	0			0	-	-		-	0	
	Subcontracting	0	0	0			0	-	-		-	0	
	Computing	0	0	0			0	-	-		-	0	
	Other	0	0	0			0	-	-		-	0	
	total	**65,000**	**11,462**	***18,751***	***0***		**30,213**	***17.6%***	***46.5%***			34,787	
	Personnel	40,290	8,071	11,893			19,964	20.0%	49.6%			20,326	
	Overhead	25762	4,913	7,576			12,489	19.1%	48.5%			13,273	
	Travel	3948	1,339	261			1,600	33.9%	40.5%			2,348	
	Durable Eqmt	0	0	0			0	-	-		-	0	
Framatome GmbH	Consumables	0	0	0			0	-	-		-	0	
	Subcontracting	0	0	0			0	-	-		-	0	
	Computing	0	0	0			0	-	-		-	0	
	Other	0	0	0			0	-	-		-	0	
	total	**70,000**	**14,324**	**19,730**	***0***		**34,054**	***20.5%***	***48.6%***			35,946	
	Personnel	1,023,442	219,236	386,339	0		605,575	21.4%	59.2%			417,867	
	Overhead	849,187	227,260	336,827	0		564,087	26.8%	66.4%			285,100	
	Travel	62,718	20,589	14,665	0		35,254	32.8%	56.2%			27,464	
	Durable Eqmt	10,000	0	0	0		0	0.0%	0.0%			10,000	
TOTAL	Consumables	194,653	7,933	28,326	0		36,258	4.1%	18.6%			158,395	
	Subcontracting	20,000	0	2,951	0		2,951	0.0%	14.8%			17,049	
	Computing	0	0	0	0		0	-	-		-	0	
	Other	40,000	136	0	0		136	0.3%	0.3%			39,864	
	Grand total	2,200,000	**475,154**	**769,108**	***0***		**1,244,262**	***21.6%***	***56.6%***			955,738	

HTR-M1 Budget Follow-up Table

PARTNER	Cost Category	Budget	ACTUAL COSTS Year 1	Year 2	Year 3	Yeasr 4	Total	Total Pct. Spent (%) Year 1	Year 2	Year 4	Year 3	Remaining Budget	Comments
NNC	Personnel	107,432	33,200				33,200	30.9%	30.9%		30.9%	74,232	
	Overhead	107432	51,128				51,128	47.6%	47.6%		47.6%	56,304	
	Travel	9956	4,163				4,163	41.8%	41.8%		41.8%	5,793	
	Durable Eqmt	0	0	0			0	-	-		-	0	
	Consumables	0	0	0			0	-	-		-	0	
	Subcontracting	0	0	0			0	-	-		-	0	
	Computing	0	0	0			0	-	-		-	0	
	Other	0	0	0			0	-	-		-	0	
	total	**224,820**	**88,490**	***0***	***0***		***88,490***	***39.4%***	***39.4%***		***39.4%***	**136,330**	
Framatome.ANP	Personnel	19,879	0				0	0.0%	0.0%		0.0%	19,879	
	Overhead	17628	0				0	0.0%	0.0%		0.0%	17,628	
	Travel	2993	0				0	0.0%	0.0%		0.0%	2,993	
	Durable Eqmt	0	0	0			0	-	-		-	0	
	Consumables	0	0	0			0	-	-		-	0	
	Subcontracting	0	0	0			0	-	-		-	0	
	Computing	0	0	0			0	-	-		-	0	
	Other	0	0	0			0	-	-		-	0	
	total	**40,500**	**0**	***0***	***0***		***0***	***0.0%***	***0.0%***		***0.0%***	**40,500**	
CEA	Personnel	94,719	28,173				28,173	29.7%	29.7%		29.7%	66,546	
	Overhead	106701	22,220				22,220	20.8%	20.8%		20.8%	84,481	
	Travel	3788	0				0	0.0%	0.0%		0.0%	3,788	
	Durable Eqmt	0	0				0	-	-		-	0	
	Consumables	50000	2,774				2,774	5.5%	5.5%		5.5%	47,226	
	Subcontracting	0	0				0	-	-		-	0	
	Computing	0	0				0	-	-		-	0	
	Other	0	0				0	-	-		-	0	
	total	**255,208**	**53,167**	***0***	***0***		***53,167***	***20.8%***	***20.8%***		***20.8%***	**202,041**	
JRC	Personnel	87,523	6,474				6,474	7.4%	7.4%		7.4%	81,049	
	Overhead	32525	1,722				1,722	5.3%	5.3%		5.3%	30,803	
	Travel	9952	0				0	0.0%	0.0%		0.0%	9,952	
	Durable Eqmt	0	0				0	-	-		-	0	
	Consumables	20000	0				0	0.0%	0.0%		0.0%	20,000	
	Subcontracting	0	0				0	-	-		-	0	
	Computing	0	0				0	-	-		-	0	
	Other	0	0				0	-	-		-	0	
	total	**150,000**	**8,196**	***0***	***0***		***8,196***	***5.5%***	***5.5%***		***5.5%***	**141,804**	
NRG	Personnel	167,288	67,408				67,408	40.3%	40.3%		40.3%	99,880	
	Overhead	114712	51,343				51,343	44.8%	44.8%		44.8%	63,369	
	Travel	8000	4,875				4,875	60.9%	60.9%		60.9%	3,125	
	Durable Eqmt	20000	679				679	3.4%	3.4%		3.4%	19,321	
	Consumables	130000	2,617				2,617	2.0%	2.0%		2.0%	127,383	
	Subcontracting	5000	0				0	0.0%	0.0%		0.0%	5,000	
	Computing	0	0				0	-	-		-	0	
	Other	35000	0				0	0.0%	0.0%		0.0%	35,000	
	total	**480,000**	**126,923**	***0***	***0***		***126,923***	***26.4%***	***26.4%***		***26.4%***	**353,077**	
FZJ	Personnel	90,117	22,091				22,091	24.5%	24.5%		24.5%	68,026	
	Overhead	69368	17,563				17,563	25.3%	25.3%		25.3%	51,805	
	Travel	9995	1,639				1,639	16.4%	16.4%		16.4%	8,356	
	Durable Eqmt	0	0				0	-	-		-	0	
	Consumables	0	0				0	-	-		-	0	
	Subcontracting	0	0				0	-	-		-	0	
	Computing	0	0				0	-	-		-	0	
	Other	0	0				0	-	-		-	0	
	total	**169,480**	**41,293**	***0***	***0***		***41,293***	***24.4%***	***24.4%***		***24.4%***	**128,187**	
EA	Personnel	31,153	10,099				10,099	32.4%	32.4%		32.4%	21,054	
	Overhead	33813	10,982				10,982	32.5%	32.5%		32.5%	22,831	
	Travel	10000	3,899				3,899	39.0%	39.0%		39.0%	6,101	
	Durable Eqmt	0	0				0	-	-		-	0	
	Consumables	0	0				0	-	-		-	0	
	Subcontracting	0	0				0	-	-		-	0	
	Computing		0				0	-	-		-	0	
	Other	0	0				0	-	-		-	0	
	total	***74,966***	**24,980**	***0***	***0***		***24,980***	***33.3%***	***33.3%***		***33.3%***	**49,986**	
Framatome GmbH	Personnel	0	0	0			0	-	-		-	0	
	Overhead	0	0	0			0	-	-		-	0	
	Travel	0	0	0			0	-	-		-	0	
	Durable Eqmt	0	0	0			0	-	-		-	0	
	Consumables	0	0	0			0	-	-		-	0	
	Subcontracting	0	0	0			0	-	-		-	0	
	Computing	0	0	0			0	-	-		-	0	
	Other	0	0	0			0	-	-		-	0	
	total	***0***	***0***	***0***	***0***		***0***	***#DIV/0!***	***#DIV/0!***		***#DIV/0!***	0	
TOTAL	Personnel	598,111	160,971	0	0		160,971	26.9%	26.9%		26.9%	437,140	
	Overhead	482,179	153,235	0	0		153,235	31.8%	31.8%		31.8%	328,944	
	Travel	54,684	14,576	0	0		14,576	26.7%	26.7%		26.7%	40,108	
	Durable Eqmt	20,000	679	0	0		679	3.4%	3.4%		3.4%	19,321	
	Consumables	200,000	5,391	0	0		5,391	2.7%	2.7%		2.7%	194,609	
	Subcontracting	5,000	0	0	0		0	0.0%	0.0%		0.0%	5,000	
	Computing	0	0	0	0		0	-	-		-	0	
	Other	35,000	0	0	0		0	0.0%	0.0%		0.0%	35,000	
	Grand total	1,394,974	**334,853**	***0***	***0***		***334,853***	***24.0%***	***24.0%***		***24.0%***	**1,060,121**	

HTR-M Man Power and Progress Follow-up Table

			Planned effort					Actual		Forecast effort		Actual	
			Year 1	Year 2	Year 3	Year 4	Total	Year 1	Year 2	Year 3	Year 4	Total	%
WP1	NNC	1	734.0	746.0	290.0	270.0	2040	543.0	595.9	420.0	420.0	1138.9	55.83
	FRA	1	121.0	599.0	257.0	139.0	1116.0	162.4	696.9	117.7	139.0	859.3	76.99
	CEA	1	362	307.0	223	0	892	255.0	255.0	223.0	159.0	510.0	57.18
	JRC	1	82	197.4	277	326	882.4	123.0	262.1	165.8	331.5	385.1	43.64
	NRG	1	239	481	410	441	1571	144.9	233.5	596.3	596.3	378.4	24.09
	FZJ	1	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	-
	EA	1	152.7	150	150	145.3	598	96.5	191.0	150.0	160.5	287.5	48.07
	FRA GmbH	1	68	55.1	64	52	239.1	50.0	74.2	64.0	50.9	124.2	51.95
	Total		**1758.7**	**2535.5**	*1671.0*	*1373.3*	**7338.5**	**1374.8**	**2308.6**	*1736.8*	*1857.2*	***3683.4***	**50.19**
WP2	NNC	1	656.0	666.0	259.0	241.0	1822.0	481.0	601.1	359.0	341.0	1082.1	59.39
	FRA	1	195.0	959.0	411.0	222.0	1787	260.0	1115.7	222.0	189.0	1375.7	76.98
	CEA	1	1293	1094	796	0	3183	944.0	1325.5	796.0	117.5	2269.5	71.30
	JRC	1	233	560.6	785	925	2503.6	350.0	744.4	484.2	925.0	1094.4	43.71
	NRG	1	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	FZJ	1	217.4	181.0	9.0	9.0	416.4	209.0	240.0	9.0	9.0	449.0	107.83
	EA	1	71.3	70	70	67.7	279	44.8	89.0	70.0	75.2	133.8	47.95
	FRA GmbH	1	85	68.9	81	65	299.9	62.0	92.8	81.0	64.1	154.8	51.61
	Total		**2750.7**	**3599.5**	*2411.0*	*1529.7*	**10290.9**	**2350.8**	**4208.5**	*2021.2*	*1720.8*	**6559.3**	**63.74**
WP3	NNC	1	348.0	354.0	137.0	128.0	967	350.0	346.7	137.0	128.0	696.7	72.05
	FRA	1	39.0	192.0	82.0	44.0	357	51.9	223.4	58.0	23.7	275.3	77.12
	CEA	1	121	102	74	0	297	0.0	240.6	56.4	0.0	240.6	81.01
	JRC	1	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	NRG	1	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	-
	FZJ	1	1630.6	1359.0	68.0	68.0	3125.6	786.3	1674.1	18.0	18.0	2460.4	78.72
	EA	1	0.0	0.0	0.0	0.0	0	0.0	0.0	0.0	0.0	0.0	-
	FRA GmbH	1	0.0	0.0	0.0	0.0	0	0	0	0	0	0.0	-
	Total		**2138.6**	**2007.0**	*361.0*	*240.0*	**4746.6**	**1188.2**	**2484.8**	*269.4*	*169.7*	**3673.0**	**77.38**
Total	NNC	1	1738	1766	686	639	4829	1374.0	1543.7	916.0	889.0	2917.7	60.42
	FRA	2	355	1750	750	405	3260	474.4	2035.9	397.7	351.7	2510.3	77.00
	CEA	3	1776	1503	1093	0	4372	1199.0	1821.1	1075.4	276.5	3020.1	69.08
	JRC	4	315	758	1062	1251	3386	473.0	1006.5	650.0	1256.5	1479.5	43.69
	NRG	5	239	481	410	441	1571	144.9	233.5	596.3	596.3	378.4	24.09
	FZJ	6	1848	1540	77	77	3542	995.3	1914.1	27.0	27.0	2909.4	82.14
	EA	7	224	220	220	213	877	141.3	280.0	220.0	235.7	421.3	48.03
	FRA GmbH	8	153	124	145	117	539	112.0	167.0	145.0	115.0	279.0	51.76
	Total		**6648**	**8142**	*4443*	*3143*	**22376**	**4913.9**	**9001.8**	*4027.4*	*3747.7*	**13915.7**	**62.19**

Table 4 (cont) Analysis tables

HTR-M1 Man Power and Progress Follow-up Table

			Planned effort					Actual	Forecast effort			Actual	
			Year 1	Year 2	Year 3	Year 4	Total	Year 1	Year 2	Year 3	Year 4	Total	%
WP1	NNC	1	171.0	171.0	126.0	107.0	575	187.4	154.6	126.0	107.0	187.4	32.59
	FRA	1	60.0	60.0	60.0	29.0	209	0.0	89.0	60.0	60.0	0.0	0.00
	CEA	1	639	639.0	639	0	1917	648.0	630.0	639.0	0.0	648.0	33.80
	JRC	1	555	604	567	36	1762	96.3	604.0	604.0	457.8	96.3	5.46
	NRG	1	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	FZJ	1	155.0	132.0	104.0	4.0	395	135.0	132.0	120.0	8.0	135.0	34.18
	EA	1	40	200	200	185	625	319.0	103.0	103.0	103.0	319.0	51.04
	FRA GmbH	1	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	Total		**1620.0**	*1806.0*	*1696.0*	*361.0*	**5483**	**1385.7**	*1712.6*	*1652.0*	*735.8*	1385.7	**25.27**
WP2	NNC	1	444.0	444.0	329.0	277.0	1494	460.1	427.9	329.0	277.0	460.1	30.80
	FRA	1	40.0	40.0	40.0	19.0	139	0.0	0.0	0.0	0.0	0.0	0.00
	CEA	1	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	JRC	1	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	NRG	1	134.0	1050.0	401.0	1050.0	2635	1160.0	500.0	75.0	900.0	1160.0	44.02
	FZJ	1	618.0	528.0	422.0	14.0	1582.0	385.3	540.0	540.0	116.7	385.3	24.35
	EA	1	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	FRA GmbH	1	0	0	0	0	0	0	0	0	0	0.0	-
	Total		**1236.0**	*2062.0*	*1192.0*	*1360.0*	**5850**	**2005.4**	*1467.9*	*944.0*	*1293.7*	2005.4	**34.28**
Total	NNC	1	615	615	455	384	2069	647.5	582.5	455.0	384.0	647.5	31.30
	FRA	2	100	100	100	48	348	0.0	89.0	60.0	60.0	0.0	0.00
	CEA	3	639	639	639	0	1917	648.0	630.0	639.0	0.0	648.0	33.80
	JRC	4	555	604	567	36	1762	96.3	604.0	604.0	457.8	96.3	5.46
	NRG	5	134	1050	401	1050	2635	1160.0	500.0	75.0	900.0	1160.0	44.02
	FZJ	6	773	660	526	18	1977	520.3	672.0	660.0	124.7	520.3	26.32
	EA	7	40	200	200	185	625	319.0	102.0	102.0	102.0	319.0	51.04
	FRA GmbH	8	0	0	0	0	0	0.0	0.0	0.0	0.0	0.0	-
	Total		**2856**	3868	2888	1721	**11333**	**3391**	3179.5	2595	2028.45	3391.0	**29.92**

Figure 1. Allowable stresses for RPV materials

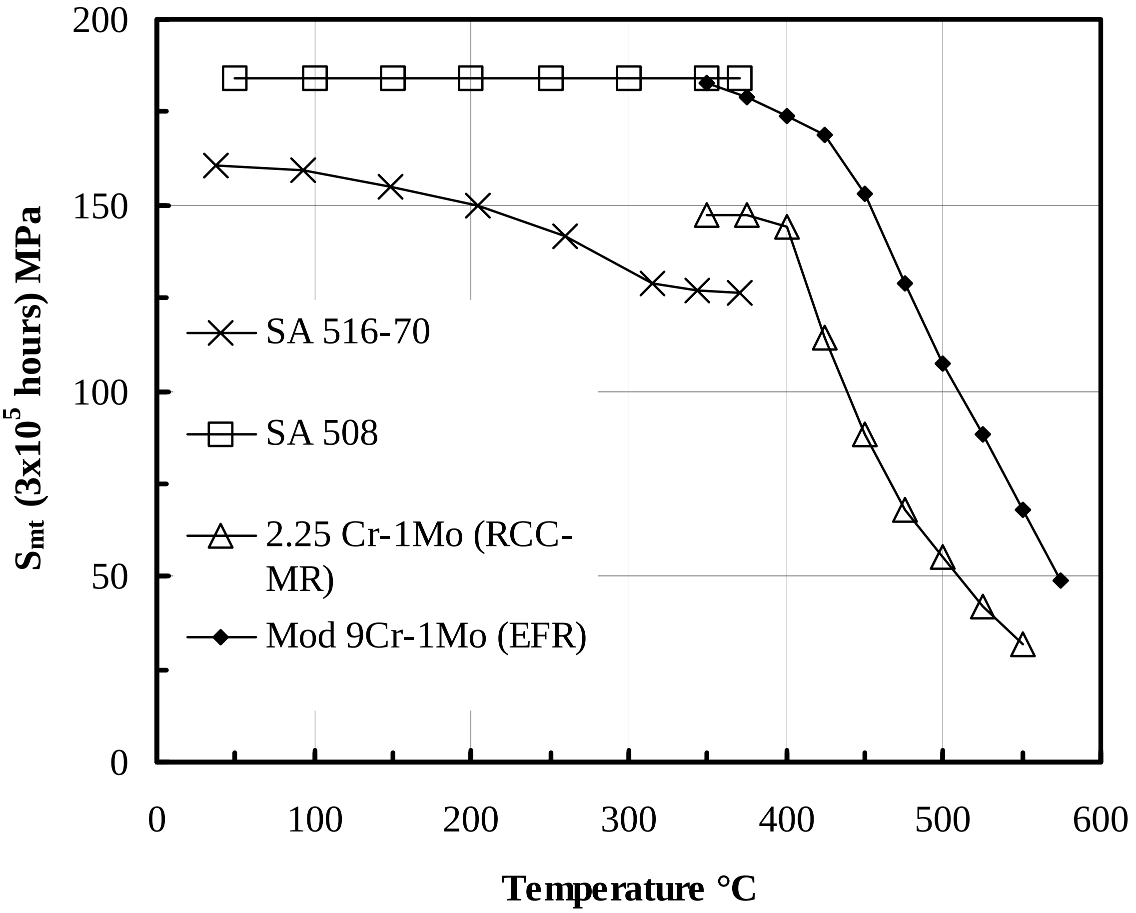
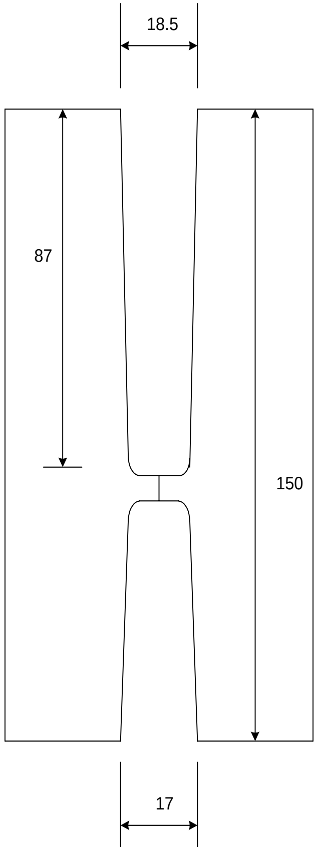
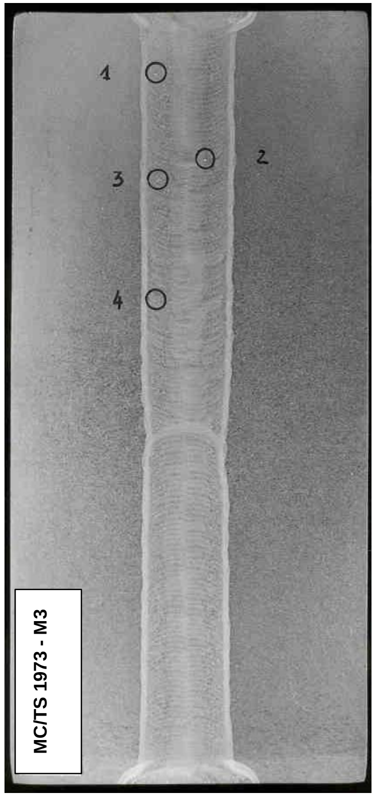


Fig. 2 Fabrication of RPV weld samples





- **<u>First welded joint</u>**

24 small cracks (≤ 0.3 mm) in the weld metal on 6600 mm² observed

- **<u>Second welded joint</u> (with lower energy)**

5 small cracks (≤ 0.3 mm) in the weld metal on 9600 mm² observed

A typical crack (n°3) 0.2 mm long

Fig. 3 Effect of irradiation on conductivity of C/C composite Material

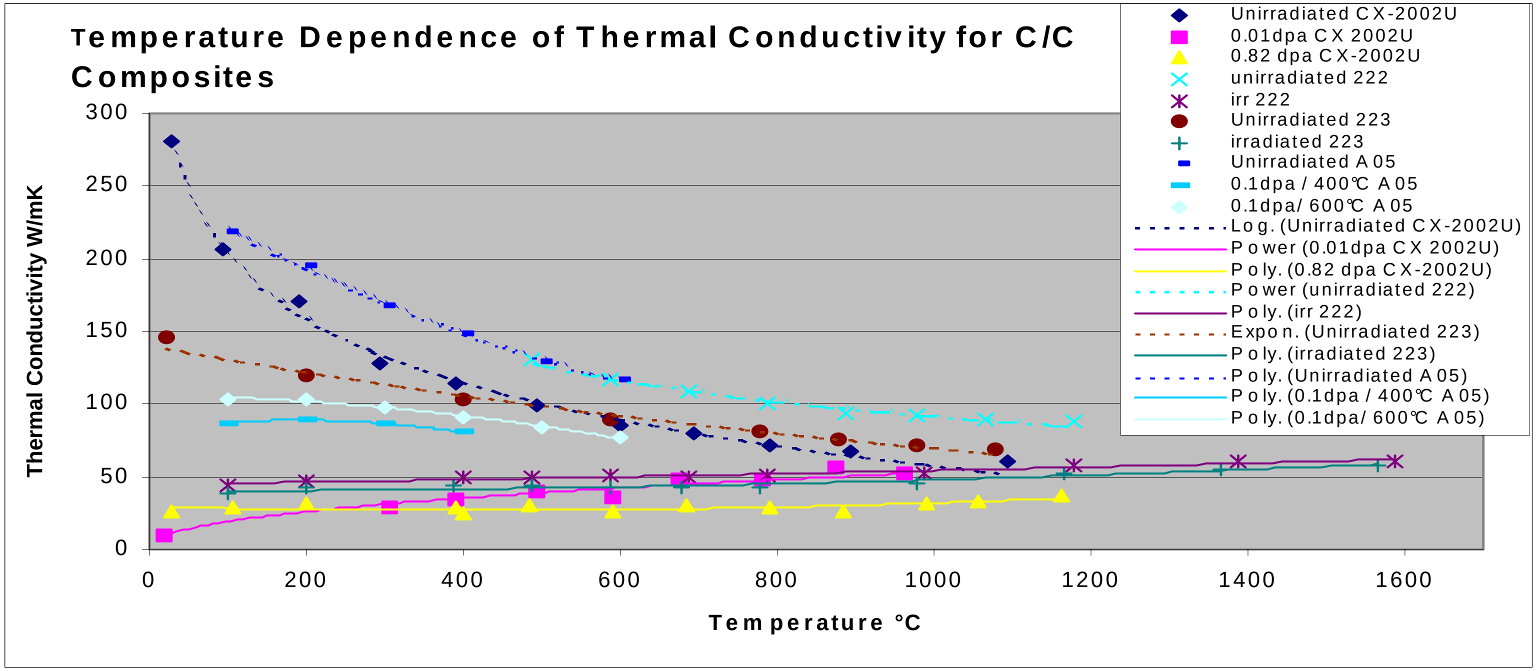


Fig. 4 Creep rupture strength of different turbine blade alloys with temperature

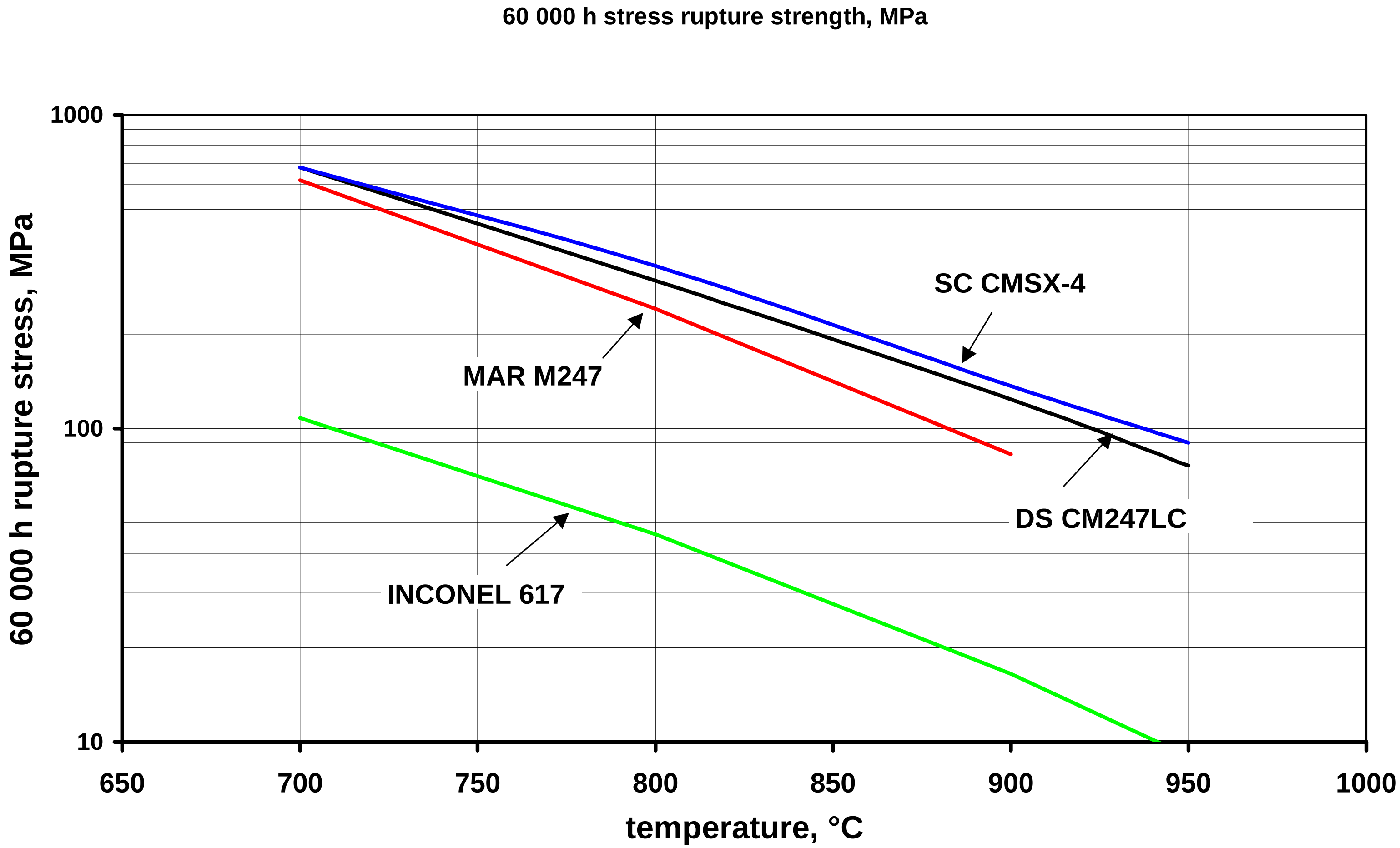
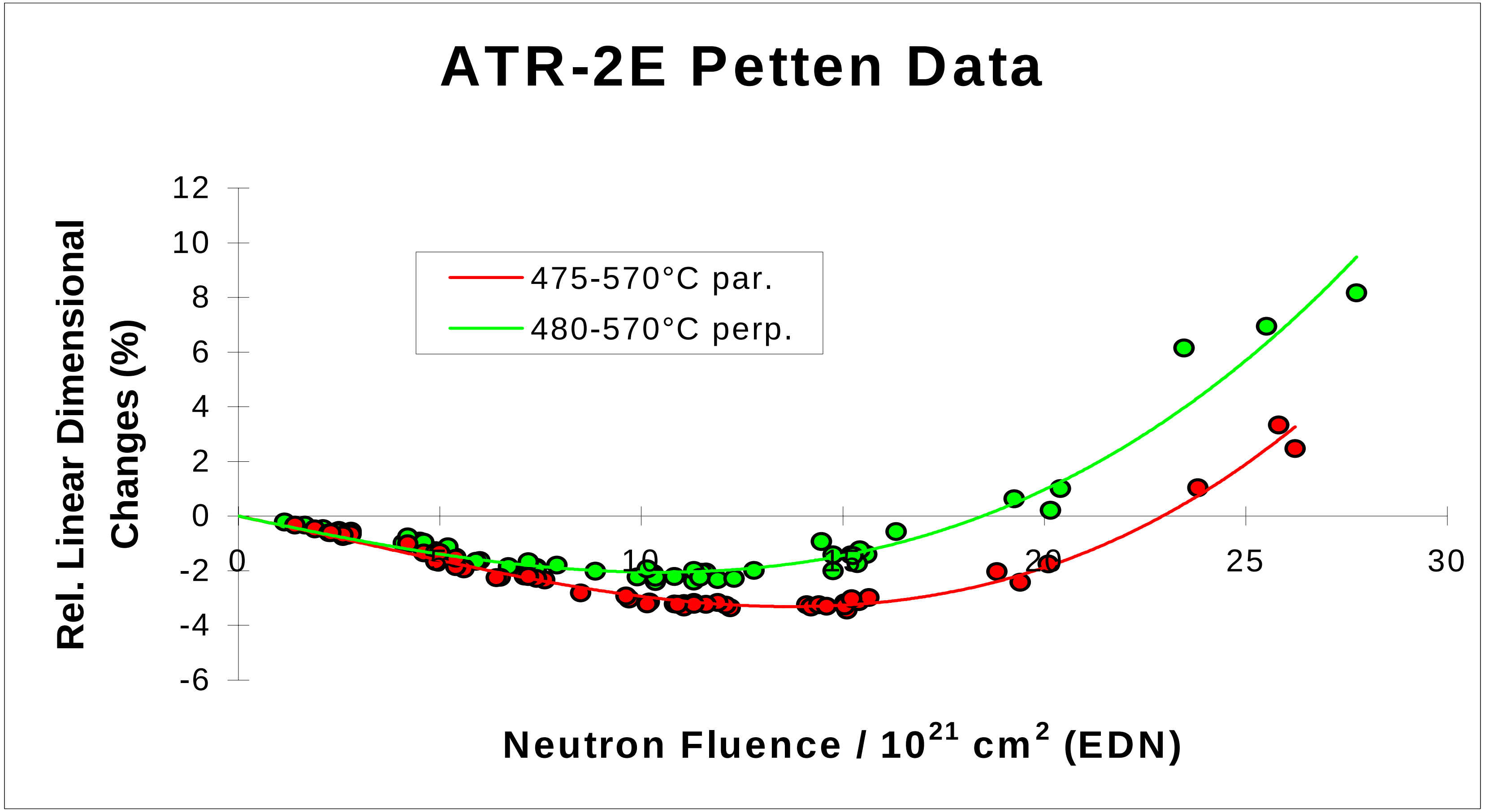
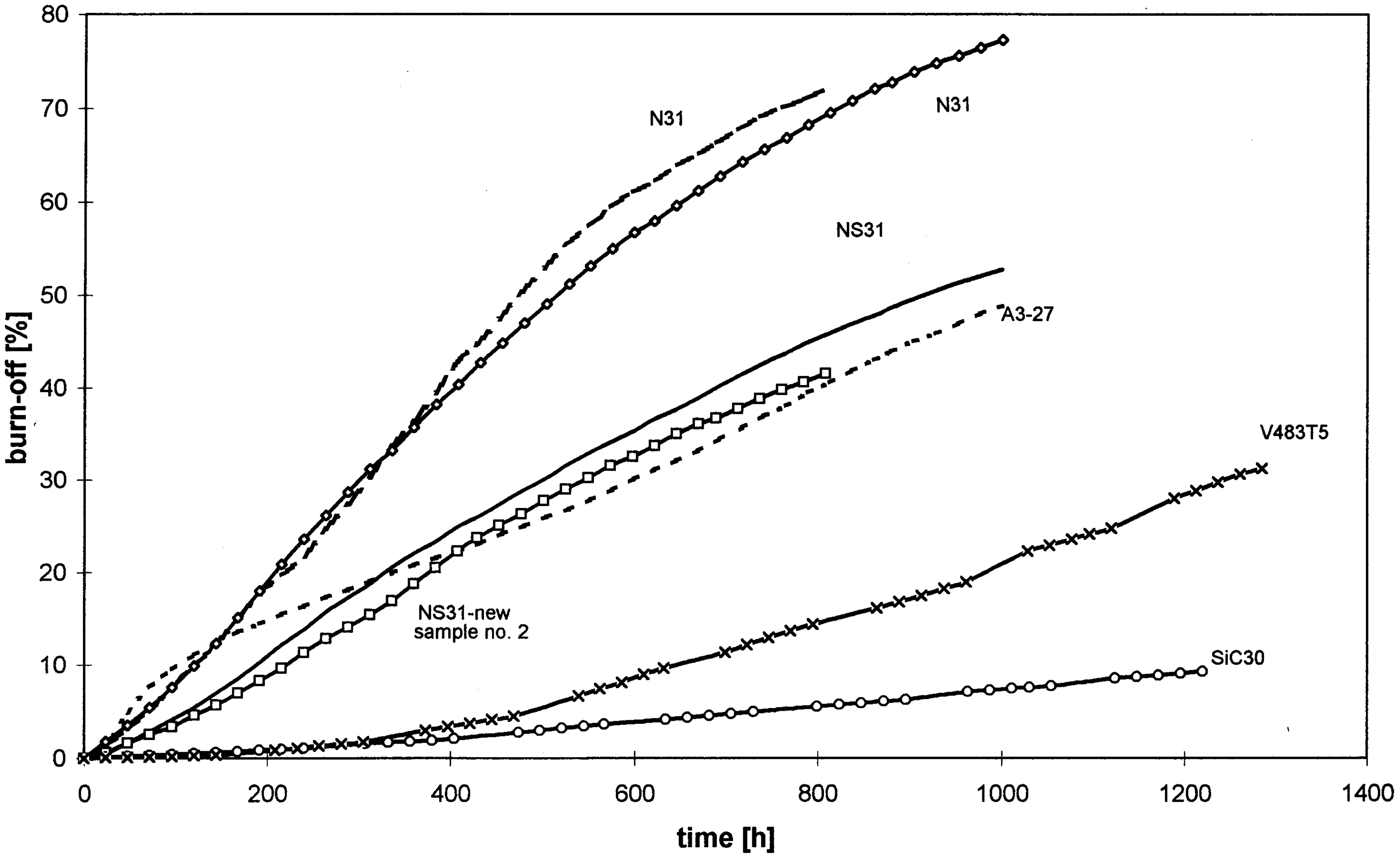


Fig. 5 Effect of irradiation on dimensional change for Graphite





Burn-off vs. time for different C-based materials in air (773 K)

Figure 7 HTR-M overall work programme
a) Project Management

ID	Task Name
1	Project Management & Co-ordination HTR-M & M1
2	Project Meetings
3	HTR-M Kick-off Meeting
4	Prepare Project Documents (HTR-M)
5	Prepare Minutes of HTR-M Kick-off meeting
6	HTR-M Progress Meeting 1 & minutes
7	HTR-M Meeting 2 & HTR-M1 KO Meeting plus minutes
8	HTR-M Meeting 3 & HTR-M1 Meeting 1 plus minutes
9	HTR-M Meeting 4 & HTR-M1 Meeting 2 plus minutes
10	HTR-M Meeting 5 & HTR-M1 Meeting 3 plus minutes
11	HTR-M Meeting 6 & HTR-M1 Meeting 4 plus minutes
12	HTR-M Meeting 7 & HTR-M1 Meeting 5 plus minutes
13	HTR-M Meeting 8 & HTR-M1 Meeting 6 plus minutes
14	Final Meeting plus minutes
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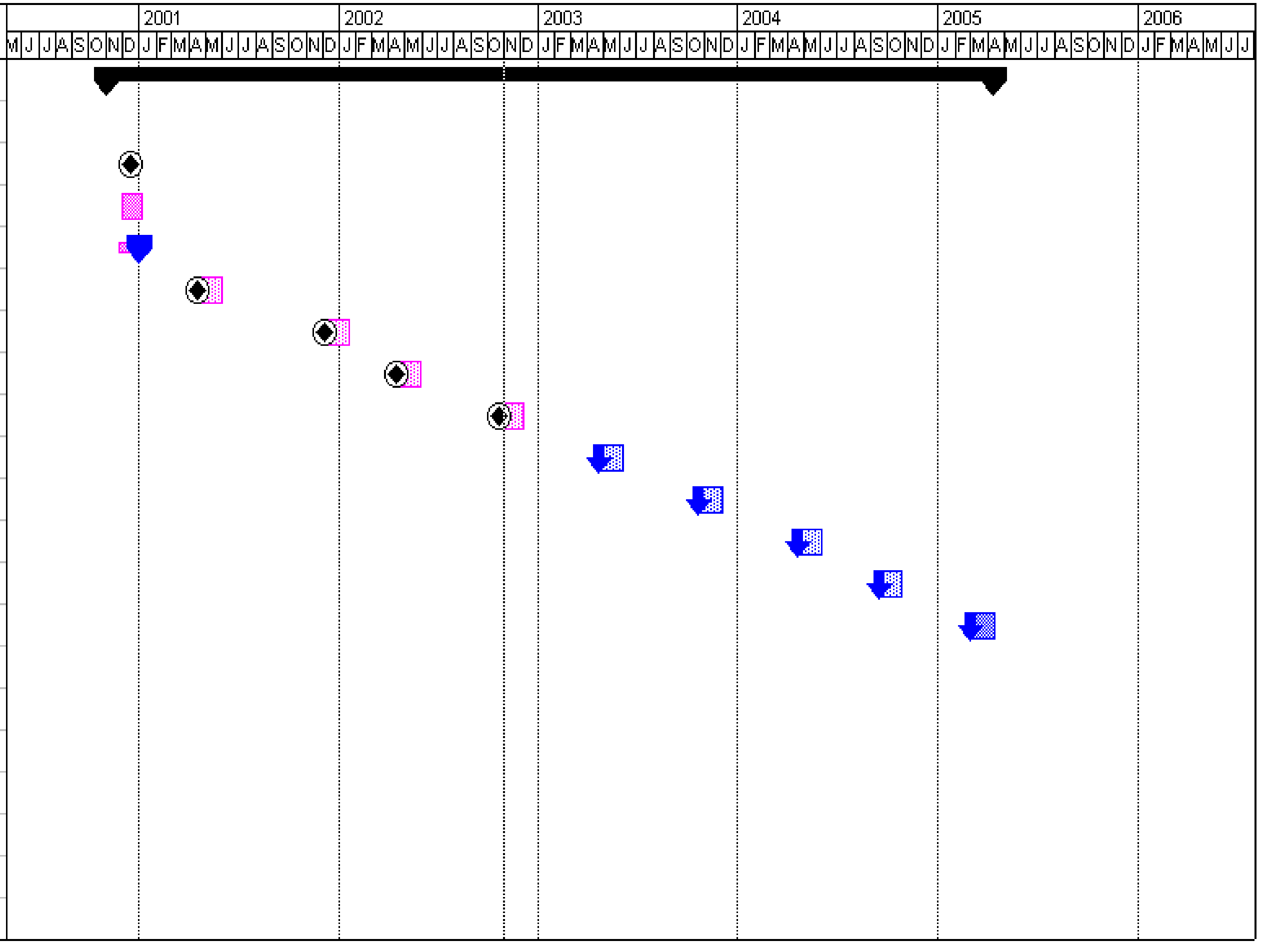

Figure 7 (cont) HTR-M overall work programme
b) TIP, management & technical reports

ID	Task Name
22	
23	Project Management & Co-ordination HTR-M & M1
24	Progress, TIP & Scientific Reports
25	First draft of TIP
26	HTR-M 6m Management Report
27	HTR-M 1st Annual Report
28	HTR-M 1st Annual Report
29	HTR-M 18 m plus HTR-M1 6m Management Report
30	HTR-M Mid Term plus HTR-M1 1st Annual report
31	HTR-M 24m plus HTR-M1 12m Management report
32	Mid Term HTR-M plus HTR-M1 TIP
33	HTR-M 30m plus HTR-M1 18m Management Report
34	HTR-M 3rd Annual plus HTR-M1 Mid term Report
35	HTR-M 36m plus HTR-M1 24m Management Report
36	HTR-M 42m plus HTR-M1 30m Management Report
37	HTR-M 48m plus HTR-M1 36m Management Report
38	HTR-M Draft Final Report
39	HTR-M Final Report
40	HTR-M1 42m Management Report
41	Final HTR-M plus HTR-M1 TIP
42	HTR-M1 Draft Final Report
43	HTR-M1 Final Report
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46	

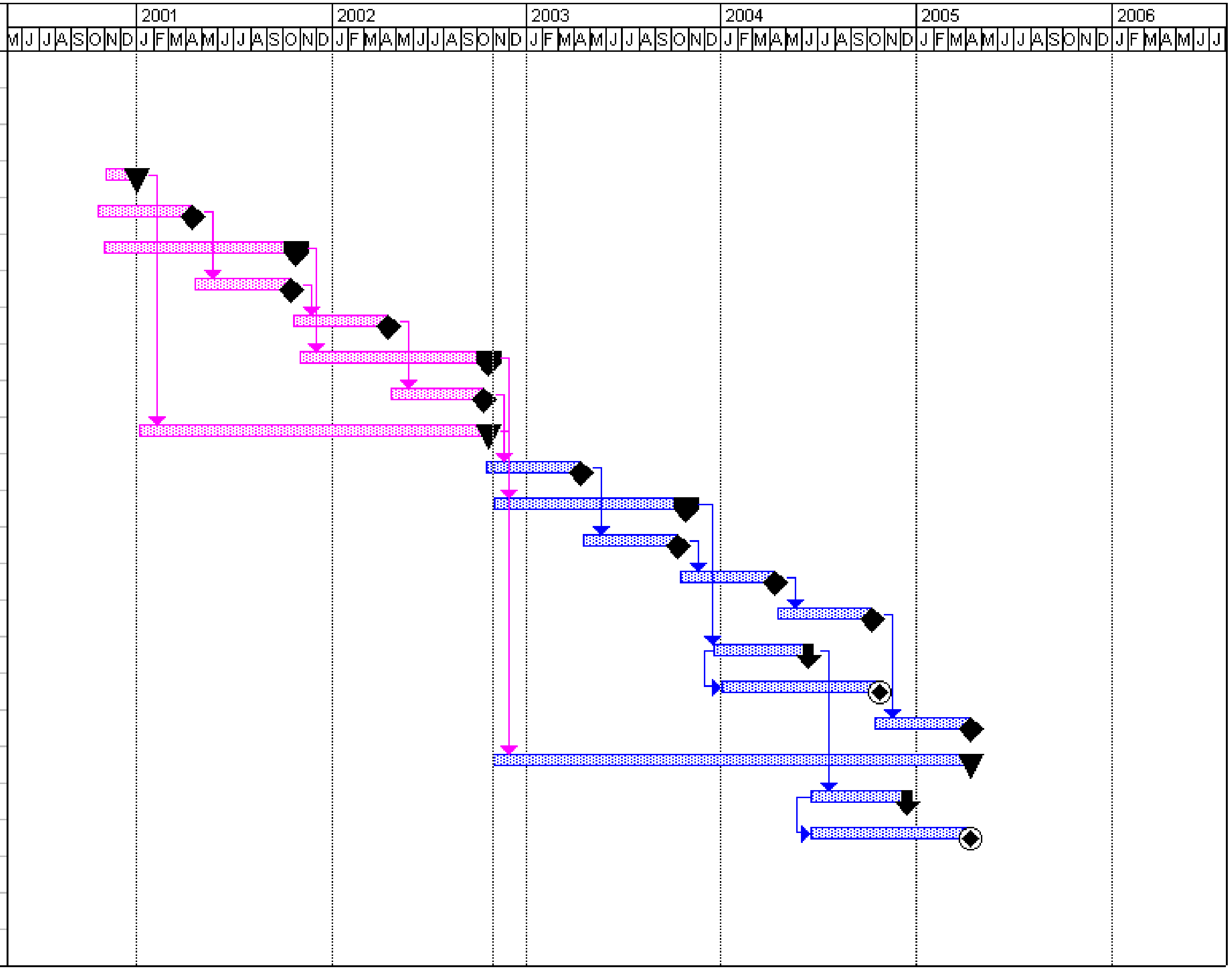

Figure 7 (cont) HTR-M & M1 overall work programme
c) Vessel Materials

ID	Task Name
47	
48	Vessel Materials - HTR-M WP1
49	Review of materials
50	Establish data Base
51	Data base for pressure vessel steels
52	State of the Art on Vessel Materials
53	Recommendations for RPV & material
54	Weld test programme
55	Irradiation & PIE
56	Synthesis
57	Factors for RPV welds
58	Irradiation data for base material & weld
59	Summary Report on vessel materials
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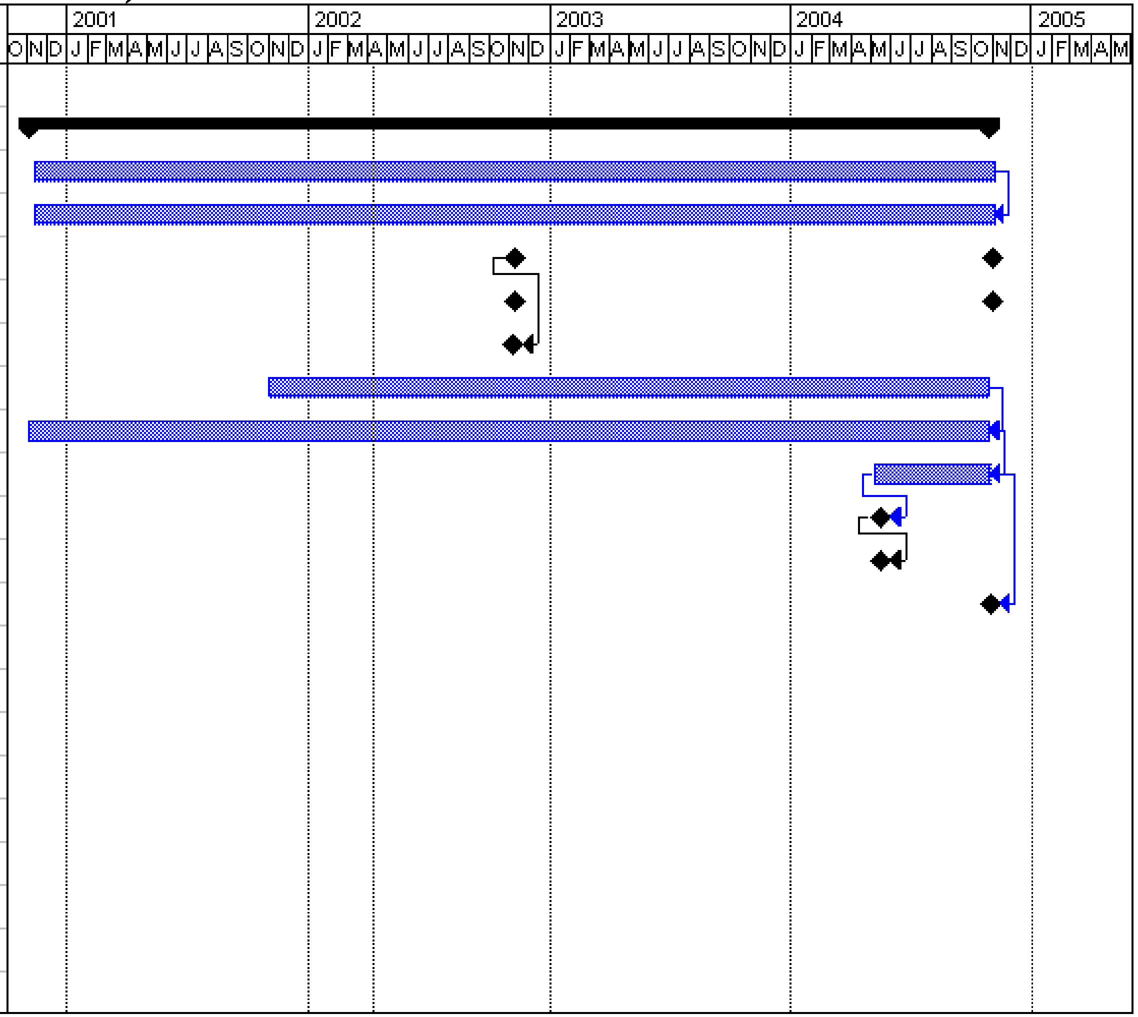

Figure 7 (cont) HTR-M & M1 overall work programme

d) Control Rod Materials

ID	Task Name
69	
70	H T - Internals (Control Rod) HTR-M WP2.1
71	Specification for internals
72	Report on specifications
73	Review / data base for internals
74	Data Base summary
75	Selection / supply / materials for internals
76	Specimens / preliminary tests for internals
77	Synthesis for internals
78	definition of testing
79	Preliminary testing
80	Final report on material
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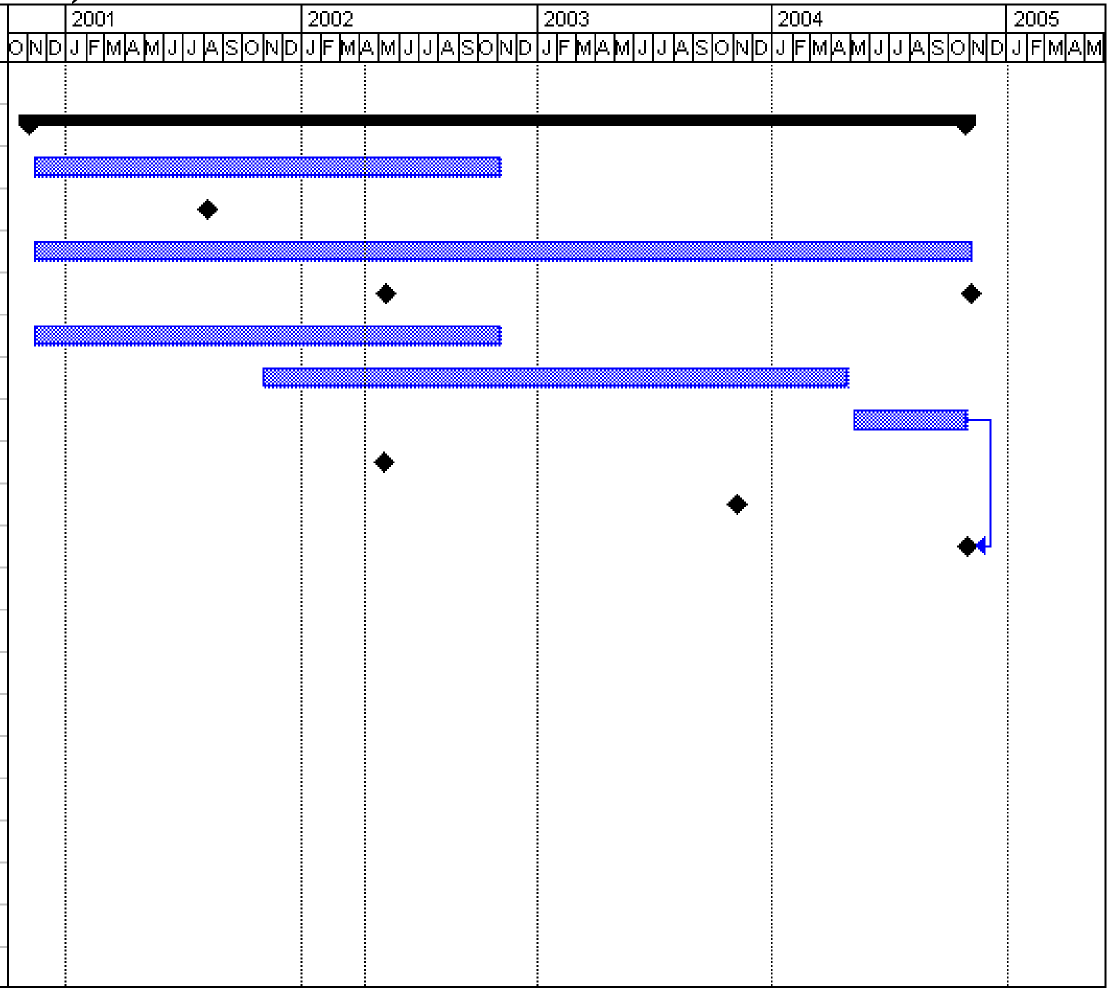

Figure 7 (cont) HTR-M & M1 overall work programme
e) Turbine Materials

ID	Task Name
92	H T Turbine materials HTR-M WP 2.2 & HTR-M1 WP 1
93	Specifications for turbine
94	Report on specifications for Turbine
95	Review / data base for Turbine
96	Materials data base for Turbine
97	Development / materials for Turbine
98	Testing / evaluation for Turbine (Short term tests)
99	Synthesis for Turbine (HTR-M)
100	Definition of testing for Turbine (Short Term tests)
101	Results of testing for Turbine (Short term)
102	HTR-M Final report on material for Turbine
103	Review of material and testing needs (HTR-M1)
104	Material procurement and specimen machining
105	Report on Selection and testing requirements
106	Report on specimen fabrication & testing requirements
107	Intermediate creep tests (HTR-M1)
108	Damage analysis & modelling
109	Synthesis & updating data base
110	Report on material testing (HTR-M1)
111	Damage analysis & modelling
112	Review of results and updating of data base (HTR-M1)
113	

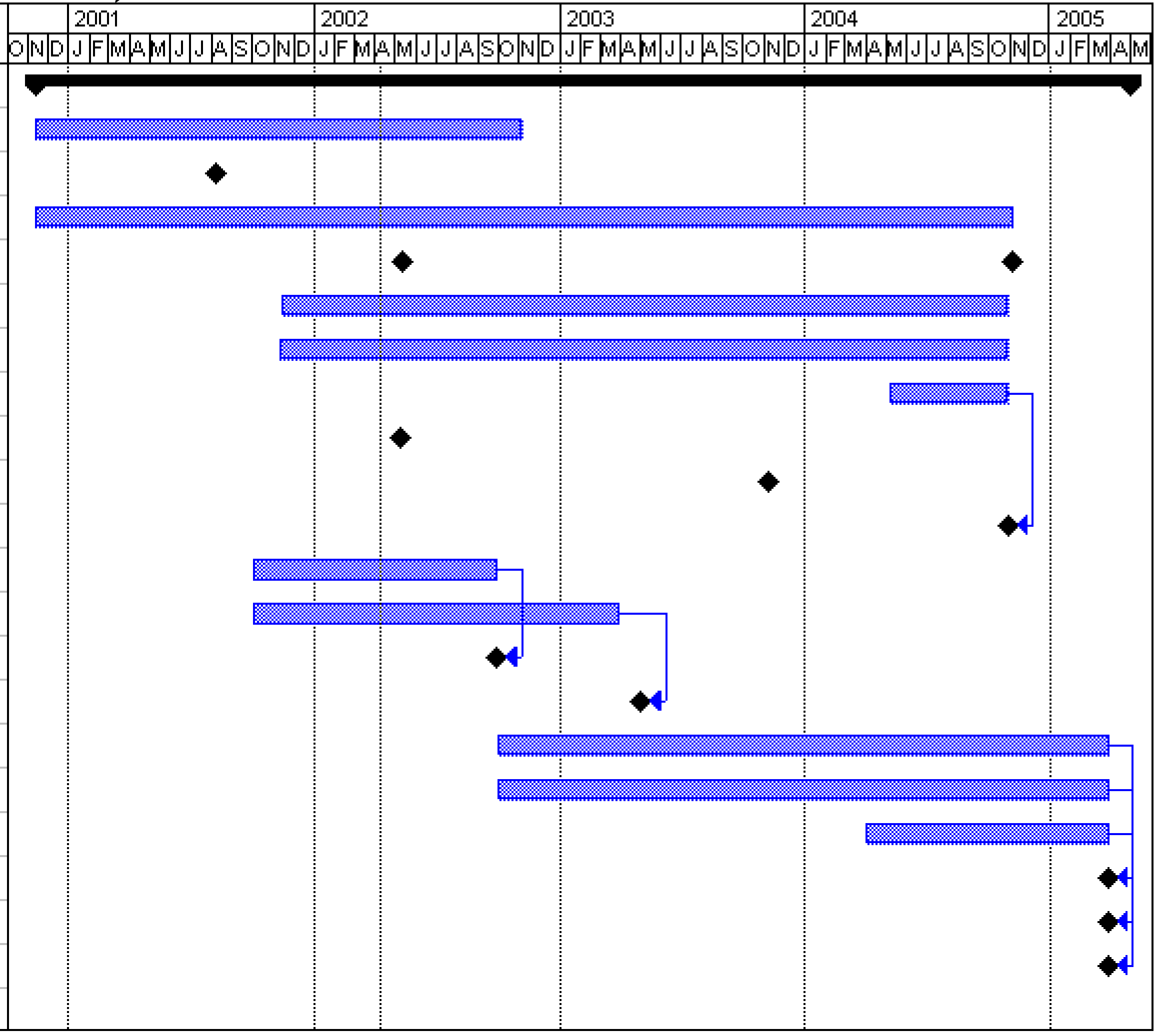

Figure 7 (cont) HTR-M & M1 overall work programme
f) Graphite review & oxidation

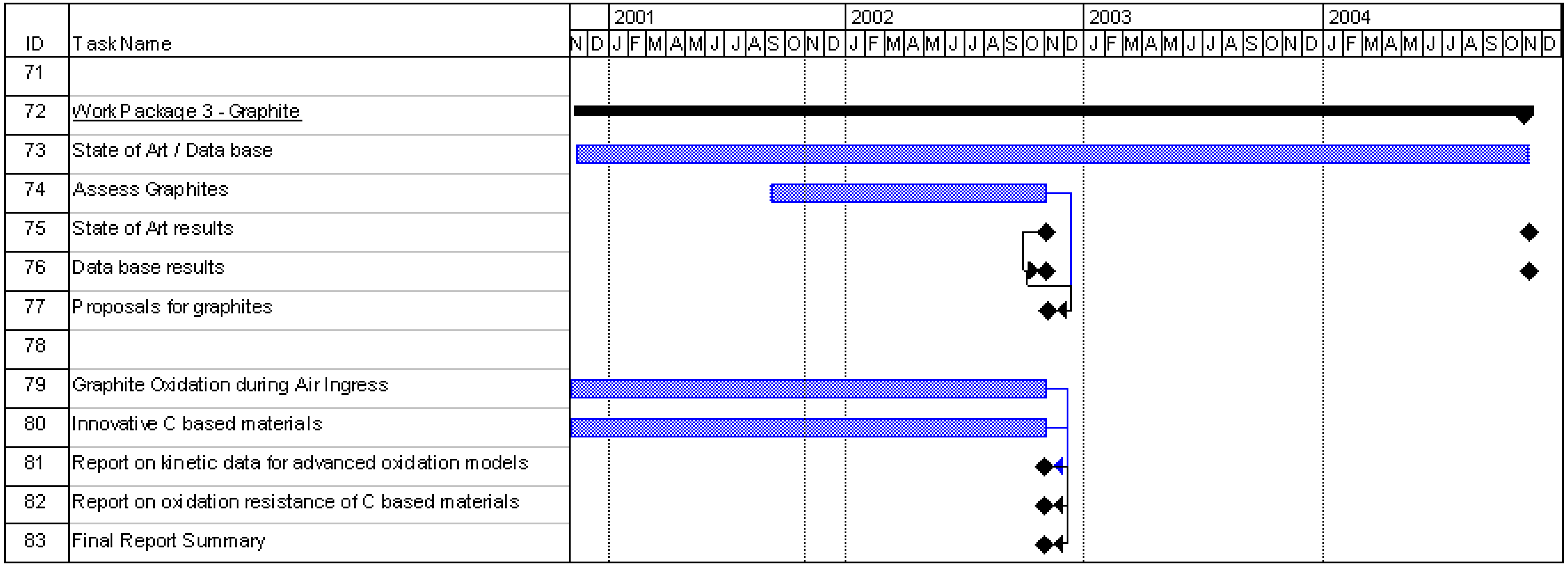

Figure 7 (cont) HTR-M & M1 overall work programme
g) Graphite irradiation