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MASTER

CURRENT STATUS OF CANADIAN ORGANIC COOLED REACTOR TECHNOLOGY

by

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ABSTRACT

Canada has been operating the first organic cooled D_2O moderated pressure tube reactor (WR-1) since November 1965. The operation of WR-1 and the supporting development programs at the Whiteshell Nuclear Research Establishment are of direct interest to those seeking to exploit the advantages of organic coolants.

The following contributions have been made which bear on the technical feasibility of the concept.

1. HB-40, a partially hydrogenated terphenyl mixture, has been used routinely in WR-1 at temperatures up to 370°C. It is now developed to the point where it is the major contender for use in a power reactor. It has the advantages of being liquid at room temperature and offering cost savings over other organic coolants at comparable conditions.

2. Zirconium base alloys can be made compatible with organic coolants provided 50ppm to 300ppm of water are added to condition the surface of the zirconium alloy against hydrogen penetration. Chlorine contamination must be controlled.

3. Fuel can be operated at practical ratings without limitations imposed by fouling provided reasonable attention is paid to coolant chemistry.

4. Non-bonded uranium carbide fuels have been taken to burnups as high as 11,000 MWd/tU and would probably be acceptable at burnups in excess of 16,000 MWd/tU.

These and other subjects associated with the current status of the technology are the subject of this paper.

The excellent performance of WR-1 indicates that, as yet, no insurmountable technical limitation faces the designers of organic cooled reactors.

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1. INTRODUCTION

The organic-cooled power reactor concept is of interest to nuclear designers because of two basic advantages over water-cooled concepts[1] [2] [3]. These are:

(i) the attainment of higher primary coolant temperature at lower pressure;

(ii) the freedom to use materials and fuels which are incompatible with high temperature water.

Canadian interest in the organic-cooled variant of the CANDU system (D_2O moderation, natural uranium fuel, pressure tube design) dates back to 1958[1]. Later comparative economic studies indicated that the BLW

(Boiling Light Water) and the organic-cooled variants held about equal promise of reducing capital costs below that of the PHW (Pressurized Heavy-Water) cooled types[4]. Because of the greater probability of establishing early technical feasibility, the BLW concept was chosen for early exploitation[5]. However, sufficient interest remained in Canada to proceed with the 40 MW(th) organic-cooled reactor (WR-1) to form the central experimental irradiation facility at the Whiteshell Nuclear Research Establishment of Atomic Energy of Canada Limited.

Originally intended as a reactor test, WR-1 emerged to fill the dual role of a test reactor and reactor test. Because this hitherto untried concept has worked so well, WR-1 has filled both roles with remarkable success. As a test reactor, it offers all of its sites for both fuel and materials experiments at temperatures and power densities of interest to power reactor designers. Simultaneously, it has given us experience with a complete organic coolant system at temperatures of practical interest.

The design of WR-1 has been described elsewhere[6]. For the purpose of this paper it is sufficient to recall that it is a heavy-water-moderated, vertical pressure tube type, with its 37 sites cooled by high temperature organic coolant. It is the first reactor of its type. As such, its performance since criticality in November 1965 has been remarkably successful. Allowing for the operating time lost to the insertion and extraction of experiments, the availability of WR-1 has been over 80% for the last twelve months.

The purpose of this paper is to summarize and report the progress which has been made in establishing the technical feasibility of the organic-cooled concept through the operation of WR-1 and the execution of the supporting development programs.

2. COOLANT TECHNOLOGY

A practical organic coolant must:

(i) have adequate thermal and radiolytic stability;

(ii) produce decomposition products which are soluble in the coolant;

(iii) be compatible with the system materials.

The economic feasibility hinges upon the cost of the coolant, its rate of consumption, and the degree of chemical control required to give adequate system performance. Ease of system operation and maintenance also affect the economics and give an incentive to use a coolant which is liquid at room temperature.

Since 1959 the Canadian organic coolant program has aimed consistently at the development of a low melting point coolant. From the start, the terphenyl family was recognized as being amongst the best for radiolytic and thermal stability, and the first Canadian reference coolant was a mixture approximating the binary eutectic of ortho and meta-terphenyls[7][8]. The commercial mixture *Santowax OM* was specified to conform closely to this composition [9]. However, the presence of para-terphenyl as an impurity resulted in a feed coolant which was solid at room temperature, having a final melting point of 60-80°C. With 10 to 30 wt.% high boiling polymeric decomposition products (HB) the coolant was a very viscous liquid at room temperature.

The specification of a maximum of 5 wt.% para-terphenyl resulted in a coolant cost[2] of $0.97/kg. Apart from its low temperature characteristics and high cost, *Santowax OM* proved to be an acceptable coolant [9][10][11][12][13].

The WR-1 reactor was designed for a low melting point coolant and is not completely trace-heated. Therefore it was necessary to commission and start up either with a synthetic blend of *Santowax OM* and HB or with an alternate liquid coolant. We chose the latter course and, after screening several candidates[14], selected a partially hydrogenated terphenyl mixture available commercially as *HB-40*[3] at a cost of $0.38/kg. Apart from its value as a startup coolant, it also offered potential for a cheap, low melting equilibrium coolant.

WR-1 has now operated with *HB-40* coolant since commissioning in November 1965. The coolant temperature has been consistently 360°C to 375°C since December 1966. The performance has been so good that *HB-40* is now the WR-1 reference coolant. It is also considered a major contender for an organic-cooled power reactor. Basic data on *HB-40* coolant have been reported in detail elsewhere[10][11][12][13][14][15][16]. In this paper, emphasis is placed on WR-1 performance and its implications for power reactors.

2.1 Coolant consumption

Experience with *HB-40* in WR-1 has borne out, to a remarkable degree, earlier predictions obtained from experiments in a small loop in the NRX reactor[15]. These were:

(i) the High Boilers formed during irradiation of *HB-40* are less stable than those from *Santowax OM*. Hence net HB production rates will be about the same in the two coolants.

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[1] Registered Trade Mark of the Monsanto Company

[2] In this paper, all costs are expressed in Canadian dollars

[3] Registered Trade Mark of the Monsanto Company

(ii) production of volatiles (boiling in the range of, or below, the boiling point of diphenyl) will be higher in *HB-40* than in *Santowax OM*, but the rate may be minimized by recycling these volatiles.

(iii) decomposition rates will decrease as HB concentrations increase.

The present decomposition rates in WR-1, at about 25% HB, are given in Table I, together with our predictions and the expected rates if the coolant were *Santowax OM*[11].

In units useful to the power reactor designer, a coolant decomposition rate of 20 g per kWh of absorbed energy corresponds to about 2.5 kg decomposed per MWd of total reactor power in a D_2O moderated pressure tube reactor.

By June 1967, the WR-1 coolant was not yet at steady state conditions. In addition, the volatile production rate was higher than predicted because the WR-1 condensers are designed to operate at high temperatures. As the steady state condition at between 30-40% HB is approached and when the necessary modifications to the condensers are completed, it is expected that a total coolant consumption rate of 2.5 to 2.8 kg/MWd will be reached. At a coolant cost of $0.38/kg, this is equivalent to a make-up cost of 0.11 to 0.12 mill/kWh for a power reactor.

An analysis of the data to date indicates that *HB-40* can probably be used at outlet temperatures at least as high at 400°C. More work is required to define the upper temperature limit.

2.2 Physical properties

Coolant physical properties depend upon system operating conditions, and are a function of temperature, high boilers and volatiles content, and total absorbed radiation dose. Density, specific heat and thermal conductivity data have been reported for *HB-40* coolant and are similar to those for terphenyl coolants[13]. Vapour pressure is strongly dependent upon dissolved gas content and volatiles concentration. The hydrogen density at 350°C is 73 mg H/cm^3 for fresh *HB-40* as compared with 51 mg H/cm^3 for terphenyls, and the present value in WR-1 is about 66 mg H/cm^3.

2.3 Autoignition temperature

The unirradiated partially hydrogenated terphenyl mixture has a lower autoignition temperature (AIT) than that of terphenyls. However, the AIT of the WR-1 coolant has gradually risen from 390°C to 425°C as HB builds in and H_2 is lost. Experience has demonstrated that satisfactory operation can be achieved as long as explosion-proof equipment is used, as in the petroleum and chemical industries, and good housekeeping is maintained to prevent coolant from accumulating in lagging where it may be subject to auto-oxidation[17]. To date we have had one fire, which was easily controlled and extinguished without equipment damage or personnel injury.

2.4 Fuel element fouling

Operation of *HB-40* in WR-1 has borne out earlier predictions that the fouling problems in *HB-40* would be no worse than in terphenyl coolants. At least three criteria have been shown to be necessary:

(i) Cl content $\leqq 0.5$ ppm;
(ii) H_2O content 100-200 ppm;
(iii) O_2 in-leakage minimized.

There has been no serious difficulty in maintaining the first two, and experience has shown how the third can be achieved. Experience has also suggested that, while side stream purification by glass spool filters and Attapulgus clay columns may be necessary be provide "non-fouling" coolant, once this condition is achieved it may be possible to operate for long periods with only the filters in the circuit.

For the past six months at an outlet temperature of 365°C, fuel operating under design conditions of $\int\lambda d\theta = 44$ W/cm (max. surface temp. $\sim$460°C) has shown that the fouling criterion of less than 25 degC temperature rise on the surface of the fuel during the fuel life can be met. Fuel irradiated to 4000 MWd/tU has been examined and the surface deposit has been found to be only a few microns in thickness.

It would appear that we are reaching the stage of knowledge analagous to that in the water-cooled reactors. We have "ad hoc" methods of controlling deposition on fuel surfaces without fully understanding the underlying mechanism. It is hoped that subsequent experimentation in WR-1 and in the U-3 loop at CRNL will lead us to a better understanding. For instance, we still have no single criterion to characterize a non-fouling coolant, nor do we know the identity of the species which is responsible for fouling when it occurs.

2.5 Cost of coolant control

In addition to fouling control, control of coolant chemistry is necessary to limit the vapour pressure by removal of decomposition gases and to limit the coolant viscosity by control of the high boiler concentration.

In WR-1 these are achieved in the degassing and vacuum distillation systems. We feel that we have not yet achieved the most economic coolant purification system and that significant advances are still to be made in this field. However, using the techniques we now apply in WR-1 we have estimated the following costs (capital and operating) for coolant control in a 200 MW(e) power station. These costs are based on an 80% load factor, 30-year life and 8% financing:

Purification (vacuum distillation)	0.028 mill/kWh(e)
Fouling control (clay columns)	0.018 " "
Analytical costs (as applied to coolant only)	0.024 " "
Total -	0.070 " "

This is comparable with the costs of water-cooled reactors of a similar size.

When assessing the relative economic merits of organic-cooled and water-cooled systems, the total penalty that can be ascribed to organic coolants for both make-up and process control is not expected to exceed 0.11 to 0.13 mills/kWh(e).

2.6 Assessment of *HB-40*

We now feel that the technology of *HB-40* is better known than that of *Santowax OM*. We will continue to use it as WR-1 coolant and to gather more data on its in-reactor behaviour. An important aspect of our coolant development program will be to demonstrate its suitability at temperatures up to 400°C.

The behaviour of *HB-40* in WR-1 has been most encouraging. The low melting point eliminates the need for trace heating and avoids many potential commissioning and operating problems. The fire hazard does not appear any higher than for terphenyl coolants as long as the system is treated with the respect due to any system using a flammable fluid. Net coolant decomposition rates are comparable to those of the terphenyls. The make-up cost is significantly lower than that for any other candidate organic coolant. The purification costs to provide a non-fouling coolant are comparable to those for any other organic or water coolant.

3. PRESSURE TUBE MATERIALS

To date, two candidates have emerged as pressure tube materials:

SAP (Sintered Aluminum Product) and zirconium-based alloys. The Canadian program has confined itself to a study of the zirconium-based alloys for the following reasons:

(i) To contain a given pressure, zirconium alloy tubes will absorb significantly fewer neutrons. Volume for volume, the zirconium alloys of interest absorb ∿50% fewer neutrons than SAP. In addition, the allowable design stress is expected to be higher than for SAP.

(ii) Production and fabrication technology is well known.

(iii) The technology has a broad application. Alloys developed for higher temperatures in organic coolants will also be of interest to high temperature water-cooled reactors for reasons which will become apparent later.

3.1 The hydrogen problem

A major Canadian contribution has been the demonstration that hydrogen uptake by zirconium alloys in organic coolants can be controlled by coolant chemistry[18][19][20]. The oxide film on zirconium alloys is an excellent barrier to the migration of hydrogen. Provided this oxide film can be kept intact, hydrogen uptake by the zirconium can be confined to acceptable limits.

Two simple precautions are necessary. First, a small amount of water (50 to 200 ppm) must be injected into the organic coolant to replenish and heal the oxide film. Second, chloride contamination of the coolant must be kept below 0.5 ppm. Both measures are practical and have been applied without difficulty throughout the operation of WR-1.

Figure 1 presents a summary of Canadian data on hydrogen uptake in zirconium alloys exposed to organic coolants under good chemical control. Although most of the data are the result of outpile tests, the few experiments which have been completed under irradiation conditions are in close agreement with the outpile data. Full scale pressure tube irradiations are now in progress on two of these alloys[10][21]. One Zircaloy-4 pressure tube and two Zr-2.5Nb tubes (83 mm internal diameter and 2.00 mm thick) have been operating in WR-1 since start-up. Coupons of the tube material suspended in the coolant circuit were analyzed in February 1967. On the assumption that the tubes picked up hydrogen at an equivalent rate, the Zircaloy-4 tube would contain 13.6 ppm and the Zr-2.5Nb tubes would contain 10.0 ppm. This compares with 16.3 ppm and 11.0 ppm respectively as calculated from Figure 1.

It is apparent that the most promising alloy yet tested for organic service is Ozhennite 0.5 (99.5% Zr, 0.2% Sn, 0.1% Nb, 0.1% Fe, 0.1%Ni)[20][22]. If full scale tests bear out the laboratory data, a pressure tube with a wall thickness of 2.5 mm would require 30 years exposure at 375°C before the hydrogen uptake approached 250 ppm. Pressure tubes of Ozhennite 0.5 are now being fabricated for insertion into WR-1 by June 1968.

3.2 Bidirectional creep under irradiation

Since July 1965, the Zircaloy-4 and Zr-2.5% Nb pressure tubes in WR-1 have been operating at a stress of approximately 330 kgf/cm^2. The internal diameter of the three tubes was carefully measured at the time of insertion and again more recently (April 1967) after 9000 hours of operation in WR-1 at temperatures between 300°C and 375°C. At the time of the second measurement the tubes had accumulated an integrated fast neutron dose (> 1 MeV) at the flux centre line of $\sim 4 \times 10^{20} n/cm^2$. The change in diameter of the tubes over this interval was only ∿0.08 mm. Although it is too early to risk a definitive statement, it is clear that in-pile creep is unlikely to exclude zirconium alloys from practical application in organic-cooled reactors. The data to date suggest that creep rates can probably be limited to 10^{-5} to 10^{-6}%/h at operating stresses between 200 kgf/cm^2 and 350 kgf/cm^2 at temperatures of 375°C and probably higher.

4. FUELS

4.1 WR-1 reference fuel: Zr-2.5 Nb clad UO_2

The reference fuel for WR-1 is Zr-2.5 Nb clad UO_2 bundles[23] (see Figure 2). This was chosen over SAP clad UO_2 because experimental radiation tests indicated that the life of SAP clad UO_2 was limited probably by a racheting mechanism, which expanded the cladding to the point of rupture at relatively low levels of exposure ∿1600 MWd/tU[24][25][26].

UO_2 is a poor choice of fuel for an organic-cooled power reactor. The combination of low thermal conductivity, high organic film coefficients, high coolant temperature and low uranium density make for an expensive fuel whose power rating is limited by high fission gas release. It was selected for WR-1 because the same production techniques and equipment could be used as are required for the CANDU-PHW fuels. In the small production lots required, it gives WR-1 the cheapest source of neutrons.

The experience with zirconium alloy cladding is another matter and is of considerable interest to the power reactor case. Whereas the nuclear designer previously had but one choice of cladding, namely SAP, he can now seriously consider a second alternative which offers greater neutron economy.

Previously, hydrogen pick-up had been considered the chief obstacle to the use of zirconium alloys as fuel cladding. Two new developments are responsible for overcoming this limitation. The first has already been discussed; i.e., coolant chemistry control. However, this alone would leave the case for zirconium alloys marginal since the high temperature of the cladding (typically 465°C) still invites a relatively high rate of hydrogen uptake (see Figure 1). The second development makes use of the thermal diffusion of hydrogen. The wire-wrap which is spot welded to the cladding operates about 30 deg C cooler than the fuel sheath. Hydrogen absorbed by the cladding diffuses to and precipitates in the cooler wire-wrap[27][28][29]. Theory predicts that until the wire-wrap has been almost completely converted to zirconium hydride, the hydrogen content of the cladding should not exceed the solubility limit. Experiment confirms that the hypothesis does in fact work. We have operated experimental fuel without failure with a hydrogen content in the wire-wrap as high a 9000 ppm. Our current data indicate that fuel can be designed for reliable operation with a hydrogen content in the wire-wrap of 4000 ppm.

The most striking proof that zirconium alloys are acceptable for service as cladding in organic coolants is the performance of the fuel charge in WR-1. Peak burnup is now at 10,800 MWd/tU after an exposure of over one and a half years. To date, we have encountered but one defect, a fabrication fault exposed early in its life.

For WR-1, where the design exposure of fuel is relatively short, Zr-2.5 Nb is probably adequate for the required service. It is now apparent that Ozhennite 0.5 would be a better choice. Our data indicate that using the hydrogen sink principle, fuel clad in Ozhennite 0.5 of 0.75 mm wall thickness should be good for an exposure of over four years at 465°C. The next charge of fuel for WR-1 will be fabricated with Ozhennite 0.5 cladding to accumulate irradiation experience.

4.2 SAP clad UC - a good power reactor fuel

If, today, we were asked to recommend a power reactor fuel for an organic system, it would have to be slightly hyperstoichiometric UC (4.8 to 5.0% C) clad in SAP. The development of this fuel has been taken to the point of full scale prototypical fuel bundle tests by both Canadian and American workers in Canadian irradiation facilities.

The most pertinent experiments, either completed or in progress, are summarized in Table II.

The important advantage of SAP as a cladding is its high thermal conductivity. This allows an effective increase in surface area of the fuel by about 50% through finning. The gains anticipated in capital costs by going to the higher power densities allowed by finning would have to be balanced against any disadvantage which SAP has with regard to neutron economy.

Earlier doubts that the low ductility of SAP might limit UC fuel life have proved to be unfounded. It is true that SAP should not be designed for strains in excess of 0.5%, especially under low strain rates[25]. The development which makes its use possible is the discovery that earlier predictions of swelling of UC under irradiation have proved to be grossly pessimistic[30].

Full scale bundle tests have accumulated 14,000 MWd/tU with no sign of difficulty. This is already sufficient to ensure low fuelling costs with a natural uranium system. We expect that natural UC of reasonable design can be produced for about $51.00/kgU, including $17.6/kg for U_3O_8. A reactor designed for 10,000 MWd/tU and 33% efficiency would have a fuelling cost of 0.64 mills/kWh(e) on a throw-away cycle.

Enriched systems would probably optimize at burnups in the range of 18,000 to 24,000 MWd/tU. Although this level of performance has not yet been proven, there is as yet no reason to doubt its feasibility. At these higher burnups, a minor sacrifice may be required with regard to effective fuel density to allow room for internal swelling.

5. OPERATING EXPERIENCE WITH WR-1

5.1 Primary circuit free of radioactive contamination

One of the outstanding features of WR-1 is the remarkable freedom from radioactive contamination in the primary circuit. This is, of course, primarily because the ^{16}N activity is very low owing to the low water content of the organic coolant. Also, with coolant chemistry controlled for fouling and zirconium compatibility, there is very little mass transfer of activated corrosion products in the mild steel primary circuit. In the room containing the primary heat exchangers and pumps the background routinely measures 1 to 2 mR/hour with the reactor at full power. Radiation levels from the primary circuit piping are consistently in the range of 2 to 5 mR/h on contact.

Defect tests and failures with UO_2 and UC fuels have not resulted in contamination of the circuit. Failures are easily identified by detection of fission product gases, which are quickly purged from the system by the degassers.

5.2 Pumps, valves and seals

Organic leakage from pump seals, valve packings, flange gaskets and *Grayloc* couplings has not proved to be a problem.

The seals on the main pumps failed shortly after start-up. Failure was caused by foreign particles, presumably from construction. No further seal leakage problems have occurred in over 11,000 hours of pump operation.

All valves in the organic system are of the extended bonnet type to reduce packing temperatures. The performance of these valves has been highly satisfactory.

The use of soft iron ring flange gaskets has been successful. This has been particularly evident on the large flanges of the Attapulgus clay columns, where the frequency of removal is relatively high.

5.3 Pressure tubes

The top loading feature of WR-1 allows the replacement of shop-fabricated pressure tube assemblies as a simple routine operation. For example, two pressure tubes developed leaks into the calandria tube annulus. One was the result of a defective weld in a stainless steel channel and the other was the result of a leaky rolled joint in an experimental Zircaloy-4 fuel channel. The leaks were identified by monitoring the CO_2 in the annuli. The replacement of pressure tubes, including fuel handling, required only 12 hours per tube. Since the primary feeders contain no isolating valves, the freezeplug technique was used to isolate the tubes. The procedure works well and is now in routine use for the installation and gauging of experimental pressure tubes.

5.4 General performance as a test reactor

Although WR-1 has had its normal complement of problems including two major spills, commissioning and operation have gone extremely well and, as indicated previously, the reactor availability is very high.

As a test reactor, it is proving to be a remarkably useful tool. The ease of replacing pressure tubes invites high utilization of the sites for full scale prototypical tests of attractive candidates. The high coolant temperature allows power reactor fuel testing not only for organic-cooled fuels, but also those designed for water-cooled service. At present 14 of the 37 pressure tube sites contain irradiation experiments.

One particularly useful observation is that the water used to control hydriding and fouling in the organic coolant behaves very much like superheated steam at the same temperature. Hence, zirconium alloys found to be compatible with the coolant must be considered as candidates for high temperature steam service. For example, the Ozhennite 0.5 development is likely to find application as cladding for advanced BLW concepts where dryout at high outlet qualities would result in sheath temperatures between 400°C and 500°C.

6. CONCLUSIONS

We now consider the coolant technology proven at 375°C. The prospects of achieving a practical operation at 400°C are excellent. The barrier between practical and impractical operation may well occur at about 425°C.

Hyperstoichiometric UC is now proven for natural uranium systems designed for average burnups in the order of 10,000 MWd/tU. For enriched systems, a moderate effort will be required to establish performance between 18,000 and 24,000 MWd/tU. The designer has a choice of cladding; either SAP, which is proven, or Ozhennite 0.5, which still needs some large scale irradiation testing. The use of adjusted uranium metal (as yet untried in organic service) would have to be considered in any natural uranium system. The high uranium density combined with low cost (estimated at $38.00/kgU completely fabricated) promises economies which cannot be ignored without evaluation.

Regarding pressure tubes, zirconium alloys must now be considered serious competitors to SAP. Again, experience is quickly increasing confidence. The risk involved in testing new pressure tubes in WR-1 is negligible. Leaks and ruptures are mere hydraulic incidents since, even at operating temperature, there is little stored energy release. Pressure tubes can be replaced in less time than it takes to replace conventional boiler tubes.

To the two basic advantages which first attracted the interest of reactor designers, we must now add a third. That is the exceptional freedom from radioactive contamination of the primary coolant circuit.

It is clear from the foregoing that the technical feasibility of the organic-cooled concept has never looked better. If, five years ago, the prospects looked as good, there is little doubt that a prototype power station would have been committed and would now be at the commissioning stage. However, one cannot ignore the momentum gained by competing established concepts in assessing the future prospects for the organic-cooled system. Whether or not the next vital stage of development can be achieved will depend largely on the skill of the engineer in making the best use of its unique advantages. The promise of improvements will have to be considerable to attract resources from competing systems. However, whereas previously the concept could be comfortably dismissed on grounds of technical feasibility, this no longer applies. The state of the art now invites serious evaluation.

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TABLE 1 - Production of Decomposition Products in WR-1

	Temp. °C	HB %	grams coolant decomposed per kWh absorbed energy to form:			
			gases	volatiles	HB	Total
HB-40 present rate May, 1967	365	25	0.7	15	18	34
HB-40 predicted	350	33	0.8	2.7	17.1	20.6
	400	33	2.2	2.7	13.8	18.7
Santowax OM predicted	350	33	0.7	v. low	19	19

TABLE II

Status of UC Experiments in Canadian Test Reactors

Experiment	Experimentor	Uranium Carbide Stoichiometry	Cladding	Maximum Heat Rating q/4π W/cm	Peak Burnup To Date MWd/tU	Status
Exp-NRU-39 Phase I	AECL	Hypostoichiometric Hyperstoichiometric Stoichiometric	Na Filled Capsules	(1100)[a] (800) (300)	25,000	Waiting examination
Exp-NRU-39 Phase II	AECL	Hypostoichiometric Hyperstoichiometric Stoichiometric	Na Filled Capsules	(1100)[a] (800) (300)	40,000	Waiting examination
Exp-NRX-721	AECL/USAEC	Hypostoichiometric Stoichiometric	Finned SAP	83	11,000	Completed
Exp-NRU-305	USAEC	Hyperstoichiometric	Finned SAP	57	10,000[b]	Completed
Exp-NRU-305 Alt. 1	USAEC	Hyperstoichiometric	Finned SAP	57	14,000[b]	Continuing
Exp-WR1-903A	AECL	Hyperstoichiometric	Zr-2.5% Nb	44	7,800	Continuing
Exp-WR1-903B	AECL	Hyperstoichiometric	Unfinned SAP	44	5,300	Continuing
Exp-WR1-951	USAEC	Hyperstoichiometric	Finned SAP	42	10,000	Continuing

a. Because heat ratings are meaningless in these experiments fuel pin temperatures are quoted instead.

b. We are indebted to the USAEC and the HWOCR Program Office for allowing us to quote the status of their experiments before they have been published by the experimentors.

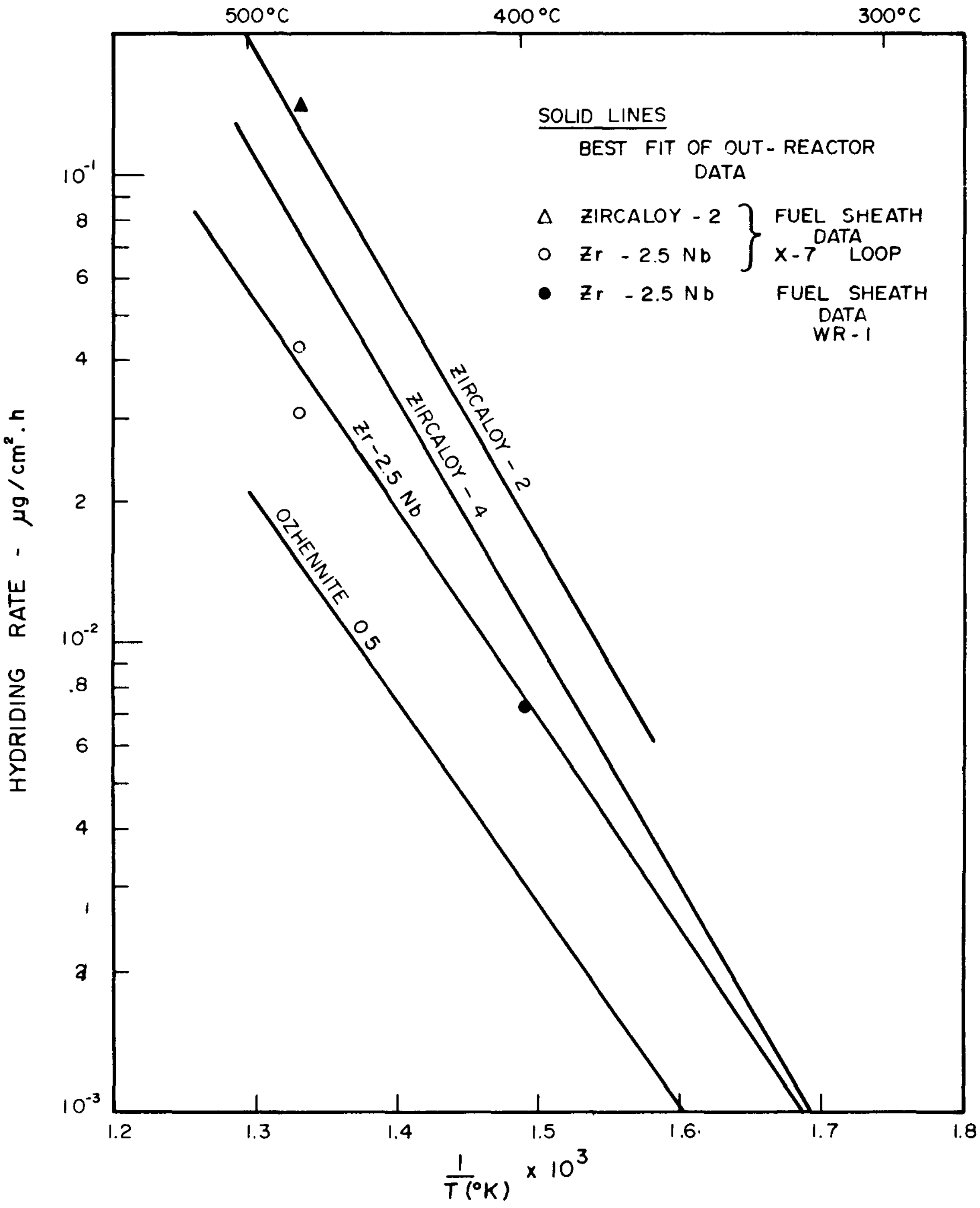

FIG. 1 : HYDRIDING OF ZIRCONIUM ALLOYS IN HB-40

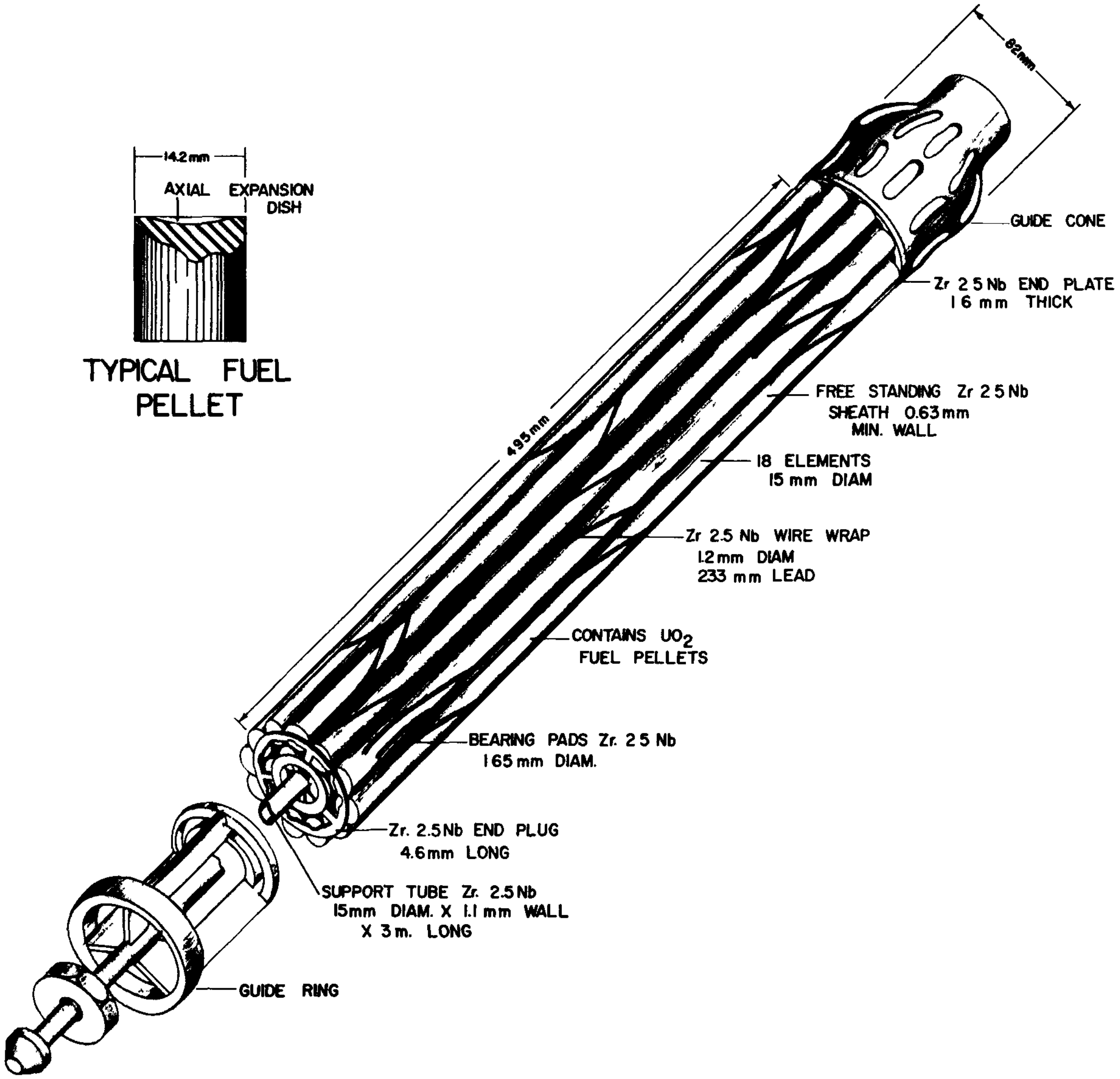

FIG. 2 WR-1 REFERENCE FUEL