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STATUS OF REACTIVITY CONTROL TECHNOLOGY
FOR
HEAVY WATER MODERATED REACTORS

June 1969

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STATUS OF REACTIVITY CONTROL TECHNOLOGY

FOR

HEAVY WATER MODERATED REACTORS

By

J. R. Worden

Systems Engineering Department
Physics and Engineering Division

June 1969

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PREFACE

This report was prepared for the U. S. Heavy Water Reactor Base Program. Its purpose is to review the status of technology in the subject area, and to identify required research and development for heavy water reactors and related systems.

STATUS OF REACTIVITY CONTROL TECHNOLOGY
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ABSTRACT

A brief review has been made of the status of technology in control system design for heavy water reactors. This review was made for the Heavy Water Program Office to assist in determining research and development requirements for control systems of large heavy water power reactors. This report includes:

1. A review of control mechanisms for heavy water reactors,
and
2. A review of control systems used in current heavy water
reactors.

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Despite the generalizations above, control system requirements are strongly dependent on specific design. The kinetic behavior of a reactor is determined primarily by the reactivity coefficients and time constants of the various components of the system. These are in turn drastically influenced by coolant choice and properties, core size, etc. As an example of overgeneralization, the neutron diffusion length in typical heavy water reactor cores is longer than in light water reactors. This feature aids in reducing spatial control requirements. On the other hand, heavy water reactors are physically much larger than light water reactor of similar power output. Consequently, despite the longer neutron diffusion length, careful analysis is required in heavy water reactors to determine requirements to control the spatial power shape.

Since the specific choice of control system is so strongly dependent on design, the present report summarizes only what is or will be done to control present or planned heavy water reactors.

In order to establish the proper context for a discussion of control systems used in heavy water reactors, a brief general discussion of the philosophy of control system design, not necessarily unique to heavy water reactors, is presented. The remainder of the report then includes:

- 1) a description of control mechanisms in current use
in heavy water reactors and
- 2) a description of control systems (combinations of the
above mechanisms) for specific heavy water reactors.

Startup Control

A control mechanism must be provided to compensate for reactivity changes occurring during reactor startups. These reactivity changes are associated primarily with temperature changes in core materials and buildup of short-term poisonous fission products, principally xenon and samarium. Control actions are required over periods of hours. Mechanisms used for startup control in present heavy water reactors include poison rods, booster rods, and soluble poison in the moderator.

Operational Control

Operational control will require control actions involving minutes, hours, and days. Control mechanisms in this category must compensate for reactivity changes associated with fuel depletion and longer-term fission product poisoning over the specified time period. In general, reactivity changes associated with routine operation are included in this category. Present heavy water reactors typically employ poison rods, moderator level variation or soluble poison in the moderator to accomplish this function.

Spatial Power Control

In order to assure safe and efficient operation of a reactor, it is essential to maintain a proper power profile over the core. This is accomplished by providing means for local control in order to suppress xenon-induced spatial oscillations or other variations in local power due to minor

variations in coolant flow, fuel burnup, etc. Required speed of response is of the order of hours. Control mechanisms in current use for heavy water reactors include poison rods, booster rods, special tubes containing soluble poison and on-line refueling.

Normal Shutdown

For purposes of bringing an operating reactor to a cold, xenon-free shutdown condition, it is necessary to essentially reverse the control requirements for startup. In present heavy water reactors, normal shutdown is accomplished by removal of moderator or by insertion of poison rods.

Emergency Shutdown

In case of emergency, it is essential that a large negative reactivity increment be introduced into the core in a few seconds. This is presently accomplished in heavy water reactors through moderator dump, poison rods or soluble poison in the moderator.

Continuous fuel shuffling is a common feature of D_2O reactors operating on a natural uranium fuel cycle. This aspect has a direct bearing on control requirements but is not considered a control mechanism as such in the present report. It is important to note however that periodic refueling, as opposed to continuous on-line refueling, will generally increase requirements for control strength. This in turn may influence choice of control mechanism. Thus, strong interaction exists between the in-core fuel management scheme and overall control requirements.

CONTROL MECHANISMS

D₂O moderated reactors have been controlled by variation of moderator level, use of soluble poison (such as boron) in the moderator, mechanical rods and various other means. The various control schemes will be reviewed in this section of the present report along with some assessment of applicability to large heavy water reactors.

Mechanical Control Rods

A review of current heavy water reactors (See Table I) shows clearly that mechanical control rods are the dominant control mechanism. Mechanical rods, whether poison or booster, can be and are used for all aspects of control discussed in the previous section. Furthermore, mechanical control rods are applicable as a control mechanisms for large reactors (1000 MW_e and larger), particularly for control of the spatial power distribution. Present designs for 500 MW_e plants such as the Pickering units⁽¹⁾ and recent design studies for even larger plants⁽²⁾ rely on mechanical rods.

Although references have been written on materials for, design and fabrication of control rods,^(3,4,5) these are quite general. No single reference was found for design of solid control rods and drives for heavy water reactors. Detailed design information must be extracted from design documents for specific plants.

TABLE I
CONTROL SYSTEMS FOR SOME
HEAVY-WATER MODERATED POWER REACTORS

<u>Boiling-Water Reactors</u>					<u>Control System</u>
<u>Reactor</u>	<u>Country</u>	<u>Date to Power</u>	<u>Net MW_e</u>	<u>Enrichment</u>	
CANDU-BLW-250	Canada	1971	250	Natural	Seven vertical control absorbers will be used to adjust flux distribution and be the basic control loop. Moderator poison for initial startup after long shutdown. Coolant flow will be varied to maintain constant coolant density. Booster rods will be used for startup and operation at low power levels. Moderator dump will be used for tripping the reactor.
SGHWR	United Kingdom	1968	97	1.24, 1.56, 2.28	This reactor uses moderator level control. The design includes 78 floodable tubes, D ₂ O, to vary moderator to fuel ratio. These tubes, however, are for experimental purposes rather than control even though the control requirements are dependent on the amount of D ₂ O in the tubes. Shutdown control is with boric acid injection into 12 additional tubes within the lattice.
Marviken	Sweden	1969	193.5	Boil: 1.35 Superheat: 1.75	This reactor is to use control rods entirely. The rods are to be Ag-Cd absorber elements in stainless cladding. There are to be 24 safety rods which are either in or out of the core. The 16 control rods have various degrees of absorbing strength and can be positioned at 55 mm insertion increments.
<u>Pressurized-Water Reactors</u>					
NPD	Canada	1962	22	Natural	Basic control loop controls moderator level. A booster rod is available for poison override.

TABLE I (contd.)

<u>Reactor</u>	<u>Country</u>	<u>Date to Power</u>	<u>Net MW_e</u>	<u>Enrich- ment</u>	<u>Control System</u>
<u>Pressurized-Water Reactors (Contd.)</u>					
Douglas Point	Canada	1966	200	Natural	Absorber rods are the primary means for control. Booster rods are available to overcome Xe buildup. Moderator poison (H_2BO_3) is used to compensate for absence of Xe or to control excess reactivity of adding fuel. Moderator level is lowered if the required decrease in reactivity exceeds the absorber rod capacity.
Pickering	Canada	1971	500 x 2	Natural	Fourteen chambers in the reactor which can be filled with H_2O will be used to control neutron flux instability. Neutron absorbing elements will be used for flux shaping and removed to provide reactivity if required. A combined shut-off rod dump system will be used to trip the reactor. Moderator poison will be used following long shutdowns and booster rods will be available.
MZFR	West Germany	1966	50	Natural	Shimming is accomplished by adjusting moderator temperature with only one control rod required for control purposes. Sixteen additional control rods are used for reactor shutdown. The rods are Cd-In-Ag.
RAPP-1	India	1969	200	Natural	The control system is to be very similar to the Douglas Point system.
KANNUP	Pakistan	1970	125	Natural	This reactor uses absorbers, boosters, moderator level and poison in the moderator as described for Douglas Point.
Agesta	Sweden	1964	9 + 55 heat	Natural	29 control rods of 30% Ag, 15% In, and 5% Cd are the major control means. Two are for fine control, 16 for coarse control and 11 for safety. The rods fall into the reactor on release of the hydraulic pressure on the chucks which hold and position the rods.

TABLE I (contd.)

<u>Reactor</u>	<u>Country</u>	<u>Date to Power</u>	<u>Net MW_e</u>	<u>Enrich- ment</u>	<u>Control System</u>
<u>Pressurized-Water Reactors (Contd.)</u>					
CVTR	United States	1963	17 Oil Super- heat	0.947- 1.25	A combination of black and gray rods are used. Both are S.S., the black rods containing 1.5 wt% boron, the gray rods pierced with holes to obtain the desired reactivity worth. The sixteen gray rods are the primary means of controlling power output and both the gray rods and the 12 black rods are dropped into the core for scrambling. Moderator dump is provided for as a backup method.
EL-4	France	1967	73	1.65-1.4	Twenty-one control elements with stainless steel clad and B ₄ C are utilized for control.
AKB	W. Germany	1970	100	1.15	Control is done with moderator level and shutdown is accomplished by moderator dump.
Lucens	Switzerland	1967	8	0.96	Ten, with space for fourteen, Ag/Cd alloy in stainless steel clad control rods are suspended by cables from individual winches on the reactor floor. They can be individually raised and lowered and, for tripping the reactor, clutches on the winches permit the rods to fall.
PRTR	United States	1961	70 (thermal)	2	Moderator level control is used with boron in solution in the moderator for shim control and moderator dump for shutdown.

Moderator Level

The second most common control mechanism in current use for control of heavy water reactors is moderator level variation. This control mechanism is used for operational control and for both normal and emergency shutdown. Control of moderator level is effected in present designs through a gas balance system, similar to that used originally in the Plutonium Recycle Test Reactor.⁽⁶⁾

A significant advantage of moderator level control is reliability. Furthermore a major cost advantage has been realized in reactor systems utilizing this control mechanism built to date. Unfortunately it does not appear feasible to design an effective moderator level control system for large size reactors.⁽⁷⁾ This is due principally to a reduced reactivity change associated with a unit change in moderator level as core size is increased. For example, the Pickering reactors, 500 MW_e each, will employ booster rods in conjunction with moderator dump for emergency shutdown.

Obviously, moderator level control is not suitable for control of the spatial power distribution as currently employed. One solution to this problem is the modular core approach planned for the large commercial version of the Steam Generating Heavy Water Reactor (SGHWR).⁽⁸⁾ In this system, the moderator level would be controlled independently in each of several zones within the core. Technical and economic feasibility of this approach has not been established however and in fact has not been demonstrated at all to date.

Soluble Poison

The potential advantages of control by chemical poison in water reactors has been recognized for some time.⁽⁹⁾ Pressurized light water reactors⁽¹⁰⁾ as well as several heavy water reactors (including the Plutonium Recycle Test Reactor in the United States) utilize this control mechanism for some aspects of control, usually startup and power operation.

In general, experience has been good with chemical poison control.⁽¹¹⁾ No significant corrosion problems have been experienced. Also, removal of boric acid by ion exchange and purification of the moderator by borated ion exchange resin has proven effective.

Soluble poison is applicable as a control mechanism for large reactors, 500 MW_e and larger. Furthermore, the chemical poison can be channeled through special tubes in the core and thus be used for control of the spatial power distribution.

For a given core design, the moderator temperature coefficient becomes less negative as poison concentration is increased. Consequently, there is an upper limit to the amount of reactivity that can be controlled by soluble poison in the moderator during operation. Also, as is well known, use of soluble poison is generally not appropriate if the solution is allowed to boil. This would lead to undesirably noisy power operation through the fluctuating density and associated reactivity coefficient.

Other Control Methods

Mechanical rods, moderator level variation and chemical poison are by far the most common control mechanisms found in present heavy water reactors. On the other hand, literally hundreds of reactor control mechanisms have been proposed, most of which could be applicable to heavy water reactors. In only a very few cases however has the necessary development work been carried out to make these innovative control devices practical on a near-term basis. Consequently, only brief reference will be made here to a few of the more promising concepts in the author's collective opinion.

The Hy-Ball control scheme⁽¹²⁾ is representative of a class of control mechanisms in which poison material is channeled through the core via special tubes. In the case of the Hy-Ball system, poison elements (spherical or cylindrical) are inserted hydraulically into the active core through tubes. The tubes are drained, removing the poison elements by gravity. Many small tubes are employed so that a given channel operates only in the fully inserted or fully withdrawn modes. Although this concept was developed for light water reactors, the scheme should be equally applicable to heavy water reactors, particularly the pressure vessel type.

A related control scheme uses gas under variable pressure.⁽¹³⁾ The Steam Generating Heavy Water Reactor (SGHWR) employs boric acid injection into 12 tubes in the core for emergency shutdown. Numerous patent applications and

proposals have been recorded on variants of the basic scheme involving poison injection, through tubes, into the core. Choice of poison material and state (solid, liquid or gas) for a specific reactor would be strongly influenced by details of core design.

The hydrogen reactivity control concept (H-Rho)⁽¹⁴⁾ is a unique mechanism in that it is mechanically passive. Furthermore, in light water systems where the concept has been demonstrated, it is self-regulating.

The H-Rho concept, particularly useful for normal power operation, is based on mass transport of hydrogen between an in-core zirconium hydride bed and an out-of-core zirconium hydride reservoir. By allowing the in-core bed temperature to vary with the thermal load while the reservoir temperature is held constant, hydrogen is transported into and out of the reactor core. This variation of hydrogen concentrations within the in-core bed provides the reactor control. In a light water system, the hydrogen (moderator) would be removed from the core as the core temperature increased, thus giving a negative reactivity effect (for typical slightly-undermoderated cores). In typical heavy water systems, the removal of hydrogen would give a positive reactivity effect. Modifications of design, both of the core and of the H-Rho device itself are possible to solve this problem. Considerable development work would be required however. Consequently, despite the obvious merits of such a control device, it will probably not be available for near-term commercial application in heavy water reactors.

CONTROL SYSTEMS

We have surveyed (Table I) the state-of-the-art of control methods which appear in current heavy water reactor designs, in reactors already in operation, and for those in which development or construction is substantially underway. As might be expected, heavy water reactor designers have made use of a wide variety of control schemes in the several pioneering machines that have been built. Typically, a combination of control methods is used with some overlapping of each type in regard to purpose and area of usage.

In many cases a particular control mechanism is emphasized to such a degree that normally complementary controls, while surviving in the final design, become rather vestigial and take a supplementary role. For the most part however separate mechanisms are used for separate functions.

It was to be expected also that a great deal of redundancy would appear in pioneering heavy water reactors because of their generally prototypical role. As with other reactor components for this emerging type there is an incentive to choose designs that will yield general experience and a broad base for future development. Of special interest in this regard is the effect on control system design of extending such reactors to larger size.

From this summary (Table I) it appears that the use of mechanical control rods, poison and/or booster, can be expected to dominate planning

for reactivity control. This trend takes full benefit of the legacy from the light water reactor development era.

Finally, the trend is to a large number of low-individual-worth absorbers for spatial control and nominal power operation and a small number of large-individual-worth absorbers for normal and emergency shutdown (see reference 2). Booster rods will likely be used for poison override but this in turn will depend largely on choice of fuel management scheme.

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