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SAFETY SIGNIFICANCE OF ATR PASSIVE SAFETY RESPONSE ATTRIBUTES

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ABSTRACT

The Advanced Test Reactor (ATR) at the Idaho National Engineering Laboratory was designed with some passive safety response attributes which contribute to the safety posture of the facility. The three passive safety attributes being evaluated in the paper are: 1) In-core and in-vessel natural convection cooling, 2) a passive heat sink capability of the ATR primary coolant system (PCS) for the transfer of decay power from the uninsulated piping to the confinement, and 3) gravity feed of emergency coolant makeup. The safety significance of the ATR passive safety response attributes is that the reactor can passively respond for most transients, given a reactor scram, to provide adequate decay power removal and a significant time for operator action should the normal active heat removal systems and their backup systems both fail. The ATR Interim Level 1 Probabilistic Risk Assessment (PRA) models and results were used to evaluate the significance to ATR fuel damage frequency (or probability) of the above three passive response attributes. The results of the evaluation indicate that the first attribute is a major safety characteristic of the ATR. The second attribute has a noticeable but only minor safety significance. The third attribute has no significant influence on the ATR Level 1 PRA because of the diversity and redundancy of the ATR firewater injection system (emergency coolant system).

1. ATR PASSIVE DECAY POWER REMOVAL ATTRIBUTES

Three Advanced Test Reactor (ATR) passive responses which are important for the safe removal of decay power from the fuel and primary coolant system (PCS) are:

(1) In-core and in-vessel natural convection heat removal;
(2) Decay heat transfer by natural convection and radiation from the uninsulated ATR primary piping to the confinement atmosphere and structures; and
(3) Gravity feed of emergency coolant makeup (firewater) from an overhead storage tank.

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The ATR reactor vessel, internal core tanks and piping are depicted in Fig. 1. Normal ATR core power removal is by forced downflow of subcooled water through the fuel and out through the internal vessel piping to outlet piping nozzles above the core. Decay power removal is normally accomplished by low velocity downflow from one of two parallel emergency flow pumps. The ATR core is a narrow cloverleaf arrangement of thin plate fuel elements within a beryllium reflector contained within a core-reflector tank as shown in Fig. 2. This ATR core and vessel design promotes and accomplishes adequate natural circulation of the in-vessel coolant for core decay power removal for eight hours or more following a loss of forced flow before the core may be threatened with core uncovery from boiloff and system leakage [1].

ATR power is normally transferred by forced primary flow through heat exchangers to a secondary cooling system (SCS). The SCS water is circulated through a cooling tower for atmospheric heat rejection. Both the PCS and SCS have small capacity backup pumps supplied from backup power sources. A passive PCS decay power removal or heat sink response is provided by a capability to adequately transfer decay power to the confinement atmosphere and structures for several days by natural convection and radiation heat transfer from the uninsulated PCS if the SCS capability becomes inadequate. A cutaway view of the ATR confinement and the PCS piping is in Fig. 3. Some forced primary circulation is required since the ATR coolant will not circulate through the PCS without pumping because of the piping elevation changes and pump discharge check valves.

ATR core decay power can be transferred without fuel failure with in-core natural circulation and boiling as long as the core is covered with water [2]. Emergency coolant makeup, to prevent core uncovery, is provided from the site firewater loop system to the ATR vessel at two vessel injection points, each through parallel valves automatically opened on either low vessel water level or very low (subatmospheric) pressure signals. The firewater is supplied by three firepumps, two of which are driven by diesel engines and one by an electric motor with a diesel generated backup power supply. The firewater is supplied from three water storage tanks. A passive response is obtained from an overhead storage tank which will provide sufficient emergency coolant by gravity flow for a significant period of time [2].

2. PASSIVE SAFETY BASES AND VALIDATION

The ATR in-vessel natural circulation and heat removal capability, including flow reversal from the normal down flow to buoyancy driven up flow has been demonstrated in ATR in-core thermal-hydraulic tests conducted during the initial start-up of the reactor. The data from these tests have been used to benchmark ATR RELAP5 [3] system thermal-hydraulic models which in turn have validated the same behavior for the ATR during transient loss of forced flow.

The ATR in-core thermal-hydraulic tests included a special instrumented fuel element with two double fuel plates containing imbedded fuel plate thermocouples and coolant channel thermocouples in the high power fuel location (Fig. 4). Tests were run to determine the ATR core natural convection heat removal capability and for transient flow reversal from forced downflow to natural convection upflow. These tests are summarized in Reference [4].

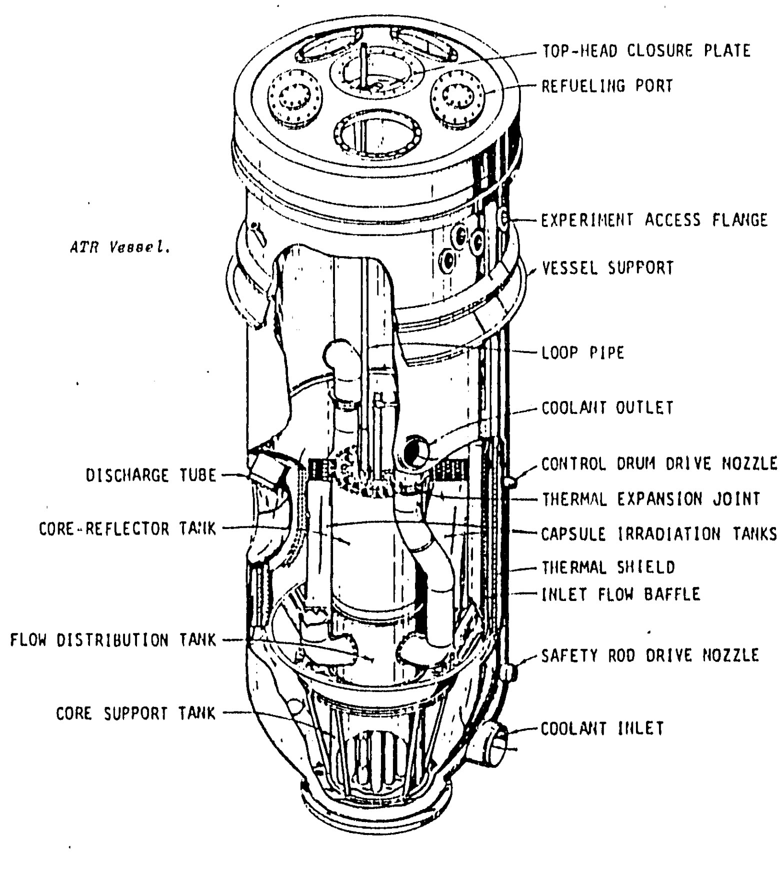

Fig. 1. ATR Reactor Vessel

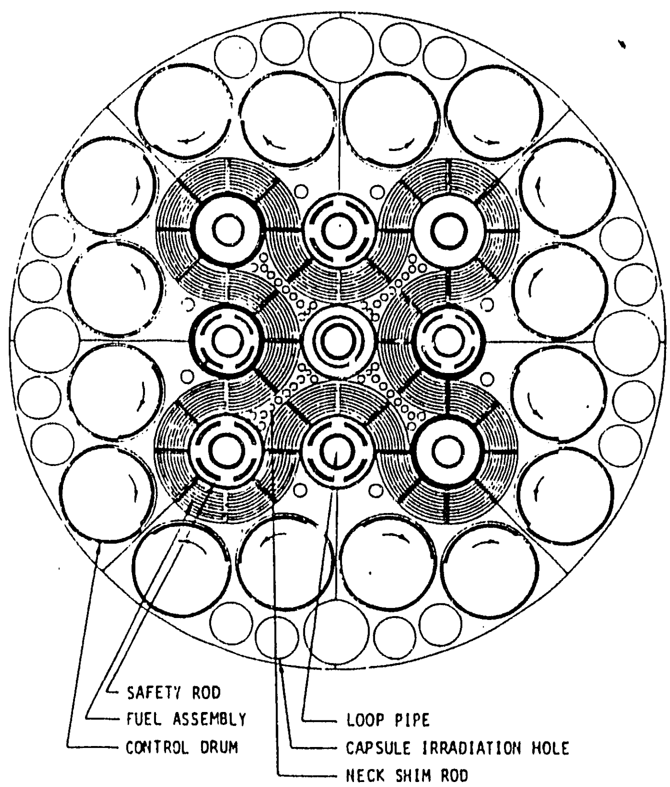

Fig. 2. ATR Core

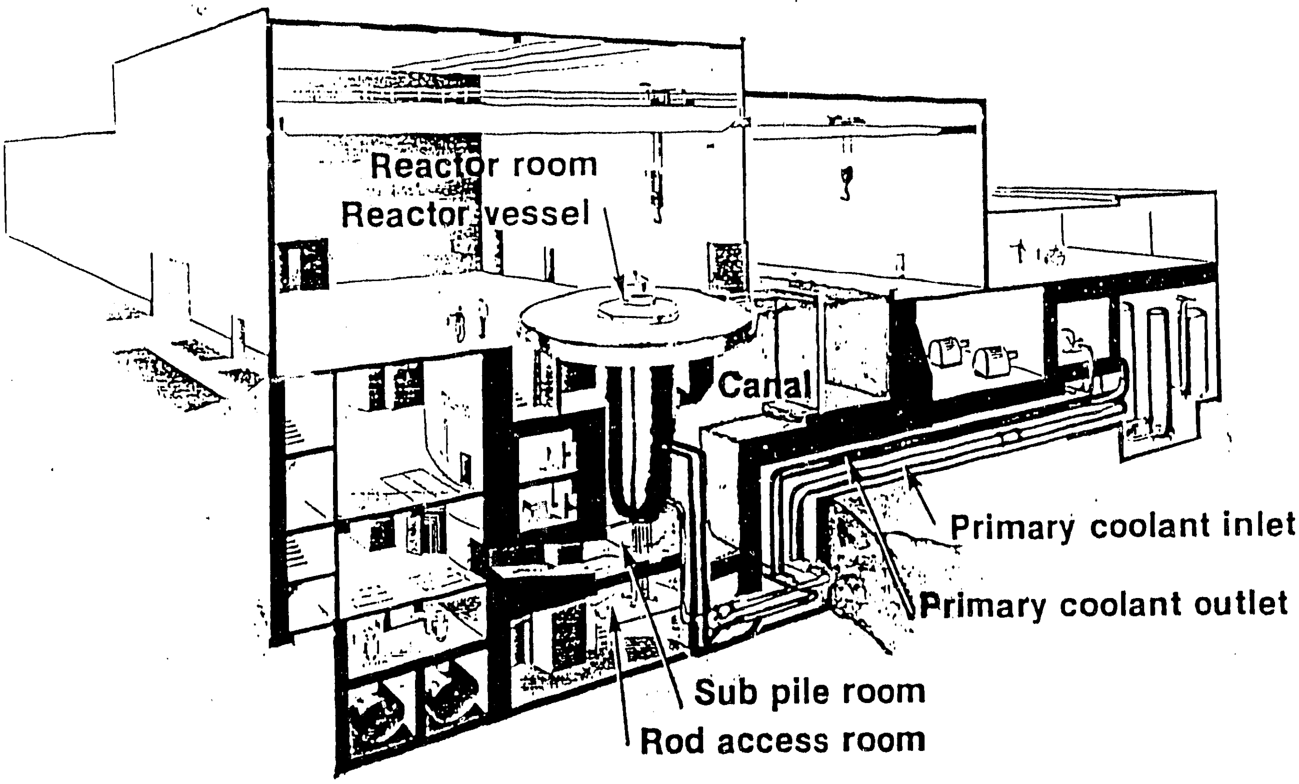

Fig. 3. ATR Confinement

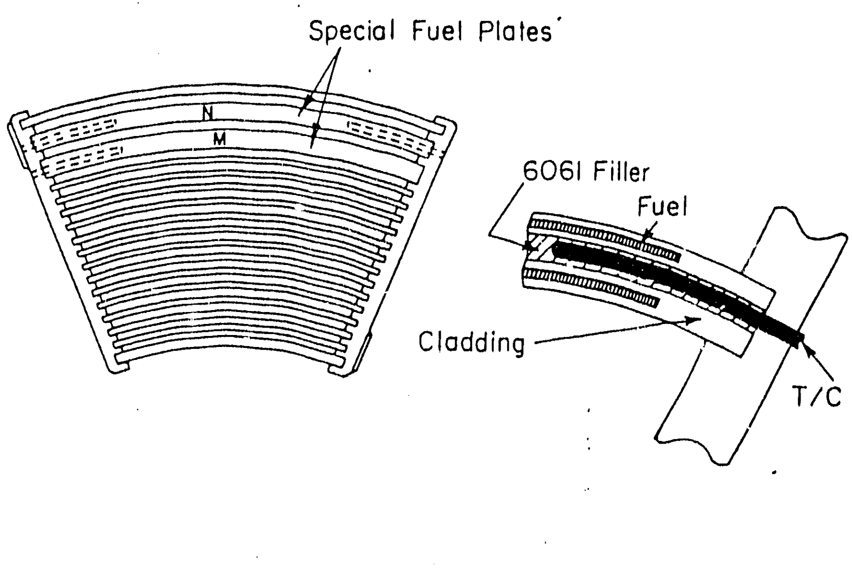

Fig. 4. Double Plate Fuel Element for Core-I Tests

The natural convection tests demonstrated that ATR decay power could be successfully removed by pressurized natural convection heat transfer within 36 s or less of reactor shutdown. Higher power tests could not be run because of temperature limitations for in-vessel instrumentation cables.

The flow reversal tests demonstrated that the transient flow transition occurred without a heat transfer crisis with a significant minimum heat transfer coefficient in the fuel[4,5]. The flow reversal tests were limited to a power of 1.43 mw, equivalent to fuel thermal conditions at one percent of full power for normal fuel plates.

The strong negative moderator temperature coefficient of reactivity prevented reactivity control for a reactor fission power greater than 1.43 mw. (Since these tests were conducted before reactor power operation, there was no significant decay power in the fuel). However, ATR RELAP system thermal-hydraulic analysis models have been benchmarked to the test data and used to predict that the flow reversal will successfully occur at higher power levels, including those that would exist shortly after a reactor shutdown in response to a loss of power to coolant circulation pumps [6].

ATR decay power transfer capability to the confinement without heat transfer to the SCS has been evaluated by both heat balance calculations and a conservative transient analysis.

The transient analysis, for an assumed complete loss of the SCS heat sink capability, predicted that the heat transfer from the uninsulated ATR PCS piping by natural convection to the confinement atmosphere would transfer the decay power deposited in the PCS coolant for over eight hours without reaching excessive coolant and component temperatures.

The transient analysis assumed conservative natural convection heat transfer coefficients for much of the ATR piping and neglected radiation heat transfer to the confinement structures, which is significant when compared to natural convection heat transfer to air [6]. A heat balance calculation for decay power removal 48 hours after shutdown which included radiation heat transfer and best-estimate natural convection heat transfer coefficients from piping to air predicted that the coolant and component temperatures would be acceptable without any heat transfer to the SCS.

The firewater gravity flow capability is based on firewater system flow test data which has been used to define the system hydraulic characteristics needed to predict the flow capability to the vessel [7]. The ATR emergency makeup needs are modest, being no greater that 0.044 m^3/s for the worst potential emergency makeup situation (a bottom closure failure for an empty experiment loop penetration) [2]. The firewater overhead storage tank, with a 568m^3 capacity, can supply needed firewater injection flow for six hours or longer for most situations. This passive capability adds an additional level of diversity and redundancy to the ATR emergency coolant makeup or firewater injection system.

3. SAFETY SIGNIFICANCE

The safety significance of the ATR passive safety response attributes is that the reactor can passively provide adequate decay heat removal and a significant time for operator diagnosis and safety response should the normal active heat removal systems and their backup systems both fail. The passive safety response attributes are important to the ATR PRA.

Because of the passive decay heat transfer capability from the PCS, it was unnecessary to develop failure models and event trees for the SCS, thus treating the SCS as a system unimportant to safety. More importantly, the passive responses lower the risk-importance of the ATR active response systems and provide enough operator response time for a high confidence for a successful diagnosis and response to many multiple failure scenarios.

The fuel damage risk significance of the decay power removal passive response attributes can be determined by removing any credit for the passive responses from the PRA assumptions and models, and therefore, assuming a total dependence on the active response systems (effectively removing one level of redundancy and diversity) and assessing the effect or change in the total Level 1 PRA risk or core damage frequency (CDF). This was done for the passive in-core natural circulation heat removal capability (assuming forced primary coolant circulation is required), for passive PCS decay power transfer to the confinement (assuming operation of either a secondary or backup secondary coolant pump or a feed and bleed method for decay power removal is required), and for the gravity flow of firewater from the overhead storage tank to the vessel (assuming one of three firewater pumps is required). The PRA models and results for the Interim Level 1 ATR PRA [8] were used for this evaluation. The results of this risk comparison for the influence of the ATR passive decay power removal attributes on the ATR Level 1 PRA CDF are given in Table I.

Core fuel damage was assumed to quickly occur for any event sequence in which a complete loss of forced circulation occurs for the evaluation for the safety significance of the ATR passive in-vessel natural convection capability.

The total CDF for those event sequences in which a complete loss of forced flow occurs would be increased by more than an order of magnitude, a factor of 12, without the ATR in-vessel natural convection decay power removal capability. The increase in the total CDF would be less, but still a factor of 3, due to the significant contributions to the Level 1 PRA CDF of other types of events, primarily large ruptures in the PCS or experiment loops [7]. But, the complete loss of flow sequences would become the overall dominant contributors to potential severe core fuel damage in the ATR. The influence of the in-vessel natural convection capability is, therefore, a major safety attribute of the ATR.

The influence of the passive heat sink capability of the ATR PCS on the Level 1 PRA CDF could not be directly obtained from the Level 1 PRA models or results. Alternate event trees had to be developed for the loss of heat sink events and for post-shutdown decay heat removal assumed that PCS over temperature and high PCS pressure could be reached upon SCS failure even with continued forced flow unless a feed and bleed approach for decay power removal were initiated.

The main effect of the removal of the PCS passive heat sink capability from the PRA is to add additional fuel failure sequences for continued forced circulation but SCS failure. Although decay power continues to be successfully transferred from the fuel to the circulating coolant, coolant temperature and pressure continue to increase. The high pressure condition will automatically shutdown all makeup inflow while coolant is discharged out the back pressure control valve and relief valves. The consequence of this sequence is a continued loss of coolant inventory while coolant in the core is boiling, eventually leading to a core uncovery as in the Three Mile Island small loss of coolant accident

TABLE I. CORE DAMAGE RISK SIGNIFICANCE OF ATR PASSIVE RESPONSE ATTRIBUTES

Passive Response Attribute	Total CDF Increase for ATR Level 1 PRA	Total CDF Increase for Effected Sequences	Conclusions
In-vessel natural circulation	Factor of 3	Factor of 12	Major safety attribute
PCS passive heat sink capability	4.5%	23%	Noticeable but minor influence
FIS gravity flow	No significant effect	14%	No significant influence on PRA

scenario. Operator action is required to re-institute coolant makeup and inventory control and to remove the decay power by a feed and bleed process to prevent eventual fuel damage, but 8 to over 40 hours is available for this action (or for correcting the SCS failure). If PCS failure were to be assumed to result from the high PCS temperature condition, a lower CDF would result because of the system depressurization and automatic emergency coolant injection.

The total CDF for the event sequences for which decay power removal success could be effected by a heat sink failure is estimated to be increased by 23% if a need for SCS operation for successful decay power removal is added to the ATR Level 1 PRA. The largest effect of this additional requirement is for the applicable loss of power sequences. The decay power failure CDF for a loss of off-site power would be increased by nearly 50% while the decay power failure CDF for total diesel-generator power failure would be increased by more than an order of magnitude. The total Level 1 PRA CDF is only increased, however, by 4.5%. Therefore, the passive heat sink capability of the ATR has a noticeable but minor influence on ATR safety as determined from the PRA. This result is influenced by the expected low frequency for a total SCS failure (loss of power increases this frequency significantly), and the several options for successful feed and bleed decay power removal.

The firewater overhead tank gravity flow capability for ATR emergency coolant makeup was determined to have no significant influence on the Level 1 PRA results. Because of the significant diversity and redundancy in the firewater injection system, even without the overhead tank, the core damage sequences which include firewater injection failure paths have a low CDF, and the overhead tank is not a major contributor to the success or failure of firewater injection.

4. CONCLUSIONS

The ATR was designed with some passive safety response attributes which contribute to the safety posture of the facility. One of these attributes is a major safety response characteristic of the ATR, that is the capability to successfully remove decay power from the fuel by natural convection in the core and reactor vessel after a complete loss of forced circulation. This passive attribute has been validated by in-core thermal-hydraulic tests supplemented by detailed system thermal-hydraulic analyses. The other passive response attributes are of significantly less importance to ATR safety. The emergency coolant makeup gravity feed capability has no significant influence on the ATR Level 1 PRA. The capability to transfer decay power to the confinement from the ATR piping after failure of the normal heat sink has only a minor overall safety significance although it is important for loss of power events.

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