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Title: ATR STEAM EXPLOSION POTENTIAL

Organization: Power Reactor Programs

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Reactor Safety Analysis Manager Approval D.W. Croucher	

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PG-T-88-022

ATR STEAM EXPLOSION POTENTIAL

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September 1988

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ATR STEAM EXPLOSION POTENTIAL

1. INTRODUCTION

A detailed assessment of the potential for an energetic molten fuel coolant interaction (MFCI) or steam "explosion" in the ATR during a severe core melt accident is on-going. However, several tentative conclusions can be drawn about the potential for MFCI. Also, the potential for ATR vessel and confinement damage should a MFCI occur can be assessed based on prior analyses and evaluations.

Two severe ATR accidents are being assessed for MFCI potential: the large loss of coolant accident (LOCA), and the large reactivity initiated accident (LRIA). The basis for the MFCI potential assessment for a LOCA is for a double-ended offset shear of an inlet or outlet 36-in. diameter primary coolant pipe with core uncovery and severe core melt. The initial assessment has been for the assumption of a dry core and 100% core meltdown. The limiting 1.30$ step reactivity addition accident is the basis for the MFCI potential assessment for a LRIA. Prior analysis for the 1.30$ step accident defined a potential core melt fraction of less than 30%.[1] The potential for a steam explosion during a LOCA or LRIA and the potential consequences are discussed in the next two sections.

2. STEAM EXPLOSION POTENTIAL DURING A LOCA

The LOCA steam explosion evaluation is based on the need for four necessary conditions if a steam explosion is to occur. These conditions are:

1. A period of film boiling and coarse intermixing of fuel and coolant

2. Destabilization of film boiling by thermal and/or pressure-induced means

3. Extensive fuel fragmentation and intermixing with coolant, resulting in a large effective heat-transfer area for rapid coolant vaporization and intimate liquid-liquid contact between molten fuel and coolant

4. System constraint for pressure buildup.

While film boiling and coarse intermixing (Condition 1) can be shown to occur following a large LOCA and system constraint (Condition 4) is a possibility, the energy available to cause film boiling destabilization (Condition 2) appears to be lower than what is required. The energy required to cause small scale fragmentation of the molten aluminum (Condition 3) is difficult to postulate for the ATR geometry and conditions. Moreover, a coherent force that would cause all the fragmentation to occur at the same time does not appear possible. Thus, meeting Condition 3 in the ATR is not likely. Therefore, based on the first assessment, there appears to be a low probability for a steam explosion as a consequence of a large LOCA.

Additional assessments will be made based on more recent large LOCA analysis results for both smaller core melt fractions and higher molten material temperatures. The possibility of localized detonation and propagation will be considered. However, for a large LOCA it appears that a significant external trigger would be necessary to initiate a MFCI or steam explosion in the ATR for a large LOCA.

If a steam explosion were to occur, the vessel is unlikely to fail (rupture) for such an event. As discussed in the ATR SAR,[2] the energy release required to fail the ATR vessel is between 236 MW-s and 1500 MW-s depending upon whether the explosive energy is released in microseconds or in about a millisecond, and depending on the test data used for the evaluation. Since steam explosions occur in milliseconds rather than microseconds, the energy release required to fail the ATR vessel is expected to be on the order of 1500 MW-s, significantly greater than 236 MW-s.

A conservative estimate for the potential energy release from a MFCI during an ATR large LOCA can be made using the following rationale.

1. Assume 100% core meltdown of the entire fuel assemblies (a 100% core melt event is unlikely to include the upper endbox or all of the sideplates). There are 40 fuel assemblies weighing 22 lb each (primarily aluminum) or 880 lb total.

2. Energy within the fuel to raise the temperature from 200 °F to melting (~1200°F) is

   0.09 BTU/lbm°F * 1000°F * 880 lbm = 79,200 BTU or 84 MW-s.

3. The energy required to melt the fuel assemblies (heat of fusion) is

   170 BTU/lbm * 880 lbm = 149,600 BTU or 158 MW-s.

4. Assume the molten material temperature increases to near the threshold temperature for significant aluminum-water reaction rates or 2138°F (1170°C). Recent large LOCA analyses indicate the molten material temperature will not significantly rise above melt temperature due to the presence of firewater injection. The energy in the fuel due to this temperature rise is

   0.26 BTU/lbm°F * 938°F * 880 lbm = 214,600 BTU or 226 MW-s.

5. The total energy in the molten fuel assemblies above a 200°F reference is 468 MW-s.

However, the maximum observed thermal-to-mechanical energy conversion during the SPERT, BORAX, and SL-1 steam explosions was 5%. A theoretical upper bound on the thermal-to-mechanical energy conversion is determined using the Hicks and Menzies correlation.[3]

1. For a 5% thermal-to-mechanical energy conversion, the energy transferred to the vessel would be 23.4 MW-s.

2. Using the Hicks and Menzies correlation, the thermal-to-mechanical energy conversion upper bound is 35% for a total energy transferred to the vessel of 164 MW-s.

These predictions result in an energy release to the vessel that is significantly below the minimum estimated for vessel failure of 236 MW-s, and even further below the region of expected vessel failure for millisecond duration pressure pulses even for the very conservative assumptions for total available energy for the MFCI. Therefore, failure of the ATR vessel is unlikely for a MFCI during an ATR LOCA.

3. STEAM EXPLOSION POTENTIAL DURING A LRIA

An assessment was made for the potential of a steam explosion for the 1.30$ step RIA based on a comparison of the predicted ATR 1.30$ step transient to power burst characteristics for the SPERT, BORAX, and SL-1 destructive reactivity excursions. The comparison is shown in Table 1. The ATR total reactivity input of 1.70$ includes 0.40$ of positive feedback from the experiment loops. Based on this comparison, it is concluded that a 1.30$ step reactivity addition in the ATR could potentially result in a MFCI or steam explosion.

Prior analyses were made for the potential pressure pulse in the vessel and the stresses at the vessel top head for a MFCI for the 1.30$ step accident.[4] These analyses were based on an estimated 20.4% core melt fraction, a 0.023 in. mean particle size for the assumed dispersed molten material, a 1832°F (1000°C) average particle temperature, and a minimum 1 ms dispersal time. The assumptions for average particle size and temperature were based on SPERT 1-D test data for a core similar to the ATR (plate-type aluminum-uranium fuel with aluminum cladding). The assumed particle temperature is, as indicated, an average. Peak temperatures of nearly 1700°C were predicted, but the assumed dispersal time is significantly less than expected for this accident. The fuel dispersal time for the SPERT-ID test is estimated to be about 25 ms. For these assummed conditions, the peak pressure pulse was 605 psi above the initial pressure or less than 995 psig and the peak stress intensity in the top head was more than 40% less than the ASME Section III faulted condition limit (the stress analysis was actually done for a 750 psi pressure pulse).[4,5,6,7,8] Therefore, the vessel is predicted not to fail due to the MFCI for the 1.30$ step accident.

TABLE 1. POWER BURST CHARACTERISTICS

Reactor	Period (ms)	Reactivity ($)	Fuel	Cladding	Fuel Mass (kg)	Cladding Mass (kg)	Water Mass (kg)	Transient Energy (MJ)	Energy/ Fuel Mass (MJ/kg)	Energy/ Metal Mass (MJ/kg)	Energy/ Total Mass (MJ/kg)	Power Peaking (max/ave)	Peak Energy/ Fuel Mass (MJ/kg)	Peak Transient Pressure (MPa)	Estimated Fuel Melting (%) and PeakTemp. (K)
BORAX-I	2.6	6	U+Al	Al	33.6	70.8	68.1	135	4.0	1.3	0.78	2.6	10.4	>41	>60 (2090)
SL-1	3.3	3.7	U+Al+2%Ni	Al+1%Ni	85.2	117.7	215	130	1.53	0.64	0.31	2.9	4.4	70	20 (2300)
SPERT 1-D	3.2	3.5	U+Al	Al	15.8	32.5	52.4	30.7	1.94	0.64	0.30	2.4	4.7	>28	43 (1700)
ATR	15	1.7	UAl_x	Al	121	149	149	164	1.36	0.61	0.39	3.6	4.9	23	20.4 (1970)

Because of uncertainties in the pressure pulse and stress analysis for the 1.30$ step, such as the consideration of higher particle temperatures and of additional melt fraction due to some metal-water reaction or core distortion, a conservative evaluation for the potential of vessel failure is based on the total transient energy for the 1.30$ power excursion. This type of evaluation is conservative by a factor of 3 relative to the Hicks and Menzies theoretical thermal-to-mechanical energy conversion limit.

Total transient energy	=	164.0 MW-s
Initial enthalpy for 250 MW	=	26.9 MW-s
Total	=	190.9 MW-s

A significant amount of energy will be transferred out of the core by the coolant; the above total neglects the coolant energy transfer.

The total energy in the core (190.9 MW-s), even if transferred to the vessel (100% thermal-to-mechanical energy conversion), would still be less than the minimum estimated energy for vessel failure, 236 MWs. Therefore, the vessel is unlikely to fail for a MFCI or steam explosion as a result of the limiting ATR 1.30$ step reactivity addition accident.

Analysis for total fuel matrix-water reaction of 38% of the available core fuel plates resulted in a predicted energy release of 1430 MW-s.[9] Such a reaction requires many seconds to many minutes at the temperatures predicted for the large RIA. Rapid reaction (ignition) occurs at 1750°C with delayed ignition possible at 1600°C. But, even at 1750°, this reaction takes more than 100 seconds.[9] Complete conversion of this energy to steam plus an additional 3500 ft^3 of hydrogen generation can pressurize the ATR confinement to 7.1 in. of water, near it's design limit of 7.5 in. This calculation did not take credit for any leakage out of the confinement during pressurization or for condensation, which will occur on the same time scale as the oxidation reaction. The potential MFCI energy due to either the large LOCA or large RIA is much less than 1430 MW-s. Therefore, even if a MFCI and vessel rupture did occur, the confinement would not be overpressured unless a local high concentration of hydrogen occurs which could lead to deflagration or detonation.

As discussed in the ATR SAR,[2] the amount of metal-water reaction observed to occur during a destructive reactivity excursion (in SPERT or SL-1) is only 0.5% to 1.5% of the total potential reaction for the fuel plates. This amounts to 7 to 20 MW-s (0.5% to 1.5% of 1431 MW-s). The participating aluminum-water reaction could increase the energy of the excursion for the 1.30$ step by 10% to 20%, not enough to threaten the vessel or the confinement.

Because of the ATR vessel geometry, it is unlikely that missiles could be generated that would threaten the confinement due to a steam explosion and vessel rupture. As seen in Figure 1, the reactor is below grade with shielding blocks over the core vessel top. Shield plugs, over the loops, are bolted down. A study for the missile potential of the shield plugs, and the need to fasten them down, is in the SAR.[10] If it is necessary to assure confinement integrity even though vessel failure is not predicted (with margin), then the missile potential of the shield plugs may need additional evaluation.

4. SUMMARY AND CONCLUSIONS

The preceding discussions of analyses and evaluations done to date for potential MFCI (steam explosions) and the potential consequences of a MFCI indicate that a significant margin exists to an ATR vessel failure threshold. Enveloping evaluations based only on core energy, and thus bypassing uncertainties in current mechanistic analyses, demonstrate the signigicant margins to the threshold of a vessel failure. Therefore should a low probability accident occur severe enough to result in a significant MFCI in the ATR core. The core damage will be retained in the vessel and the ATR vessel and confinement will adequately mitigate the rediation release.

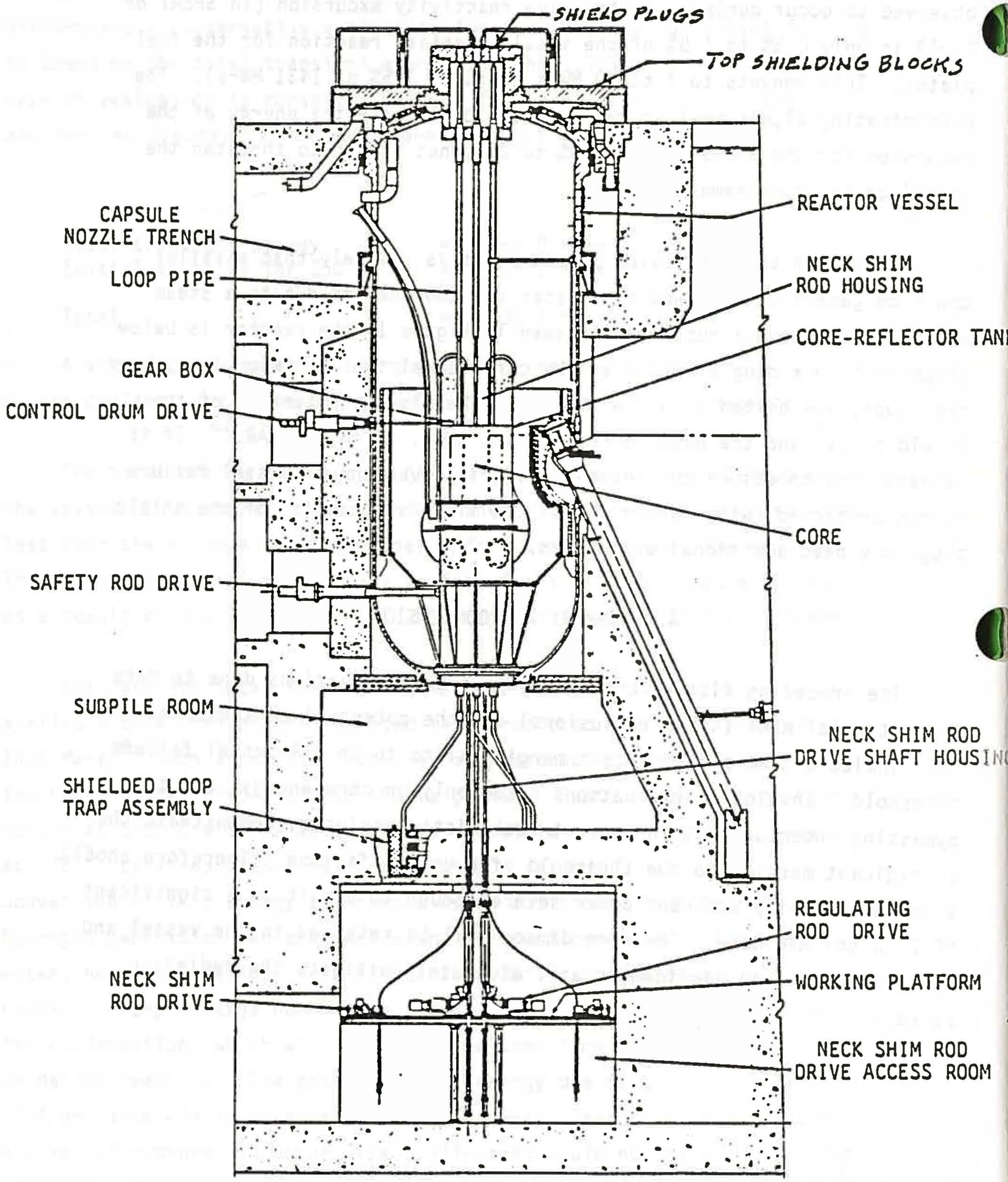

Figure 1. Vertical Cross Section of ATR Vessel, Showing the Control Drives and Part of the Shielding.

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