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An overview of FAVOR: A fracture analysis computer code for nuclear reactor pressure vessels

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ABSTRACT

One of the current tasks within United States Nuclear Regulatory Commission-funded Heavy Section Steel Technology (HSST) Program at Oak Ridge National Laboratory (ORNL) is the continuing development of the FAVOR (Fracture Analysis of Vessels: Oak Ridge) computer code. FAVOR performs deterministic and probabilistic fracture analyses of aging nuclear reactor pressure vessels (RPVs) subjected to transient conditions such as pressurized thermal shock (PTS). The initial version of FAVOR performs fracture analyses of RPVs that contain infinite length axial and/or continuous circumferential inner-surface flaws. A recent enhancement is the addition of the capability to perform fracture analyses of embrittled clad RPVs that contain axially and/or circumferentially oriented finite length semielliptical inner-surface flaws with aspect ratios (ratio of total crack length to crack depth) of 2, 6, and 10. This paper gives an overview of the capabilities of the current development version of FAVOR and illustrates a brief sampling of computational results.

1 INTRODUCTION

The motivation for developing the FAVOR code (Dickson, 1994) was to consolidate the best attributes of OCA-P (Cheverton et al., 1984) and VISA-II (Simonen et al., 1986) into a single validated, user-friendly, and well-documented RPV predictive fracture mechanics computer code that complies with the applicable regulatory criteria. The ideas used in the development of FAVOR were from lessons learned during the Integrated Pressurized Thermal Shock (IPTS) Program (Selby et al., 1985, Selby et al., 1985, and Burns et al., 1986) and the Yankee Rowe Review (Dickson et al., 1992) and Sensitivity Analysis (Dickson et al., 1993).

2 THERMAL AND STRESS SOLUTIONS

FAVOR uses the finite element method to generate one-dimensional time-dependent thermal and stress distributions (circumferential and axial) through the wall thickness of a clad RPV subjected to complex time-varying thermal-hydraulic boundary conditions. The RPV is modeled as an axisymmetric one-dimensional structure. FAVOR provides the capability for very accurate descriptions of thermal-hydraulic boundary conditions imposed on the inner-surface of the RPV wall, even for those

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complex transient definitions that exhibit discontinuities, such as pressure transients with repressurizations. FAVOR has an option for including in fracture analyses the additional axial stress associated with those transients that exhibit fluid/thermal stratification (Dickson, 1993) as predicted by specialized thermal-hydraulics codes such as REMIX (Iyer et al., 1986).

3 LINEAR ELASTIC FRACTURE MECHANICS SOLUTIONS FOR STRESS INTENSITY FACTORS

FAVOR uses stress intensity factor influence coefficients (SIFICs) and superposition techniques to calculate time-dependent K_I for various flaw depths and flaw geometries that penetrate the inner-surface of a clad RPV. ABAQUS (Hibbit et al., 1991), a nuclear quality assurance certified (NQA-1) multidimensional finite element code with fracture mechanics capabilities, was used to generate the SIFICs, applicable to clad RPVs with an internal radius to wall thickness ratio (Ri/t) of ten. This geometry is prototypical of a large percentage of the commercial pressurized water reactors (PWRs) in the United States.

A database of SIFICs was initially generated for infinite length axial and continuous 360 degree circumferential inner-surface flaw geometries. This SIFIC database was previously reported (Bryson et al., 1993). Since the initial release of FAVOR, the HSST program has generated databases of SIFICs for axially (Keeney et al., 1994) and circumferentially (Bryson et al., 1994) oriented finite length semielliptical inner-surface flaws of aspect ratios two, six, and ten. These ABAQUS-generated databases of SIFICs have been implemented into FAVOR. FAVOR now has the capability to perform fracture analyses of clad RPVs containing axially and/or circumferentially oriented flaws of aspect ratios two, six, ten, and infinity.

4 FAVOR DETERMINISTIC FRACTURE CAPABILITIES

A variety of deterministic fracture reports may be generated with FAVOR including (1) time histories of temperature, stresses, K_I, and fracture toughness values corresponding to specified flaw depths and geometries; (2) through-wall variation of temperature, stresses, K_I, and fracture toughness at specified transient times; (3) critical crack depth curves for various flaw geomtries; and (4) fracture parameter minimization. An example of fracture parameter minimization is to solve for the critical flaw depth (the minimum flaw depth that results in cleavage fracture initiation) in a RPV of specified embrittlement subjected to a specified PTS transient. Table 1 illustrates the FAVOR-generated output report for the critical flaw depths for a prototypical RPV subjected to the severe PTS benchmark transient (Bishop, 1993) evaluated at the PTS screening criterion of RT_{NDTs} = 270°F and 300°F for axially and circumferentially oriented flaws (Code of Federal Regulations, 10 CFR 50.61), respectively. The value of RT_{NDTs} is the value of RT_{NDT} at the RPV inner surface calculated according to Regulatory Guide 1.99 Revision 2. The report includes the value of RT_{NDT} at the critical flaw depth, K_I at the point on the crack front at which initiation occurs, the transient time at which initiation occurs, and the angular position on the crack front at which initiation occurs.

5 FAVOR PROBABILISTIC FRACTURE MECHANICS CAPABILITIES

Probabilistic fracture mechanics (PFM) analysis is a major element of the comprehensive probabilistic methodology endorsed by the NRC for evaluation of the integrity of PWRs subjected to PTS transients.

Table 1: Critical Flaw Depths At PTS Screening Criteria As A Function Of Flaw Geometry

ORIENTATION	ASPECT RATIO (total length/depth)	CRITICAL FLAW DEPTH (inches)	FLAW TIP RT_{NDT} (°F)	K_I ($ksi\sqrt{in}$)	TIME (min)	THETA (degrees)
AXIAL	2 to 1	0.112	269.6	38.5	21.0	0.0
AXIAL	6 to 1	0.085	269.9	39.6	22.0	90.0
AXIAL	10 to 1	0.074	270.0	39.4	22.0	90.0
AXIAL	INFINITE	0.065	270.0	39.2	22.0	90.0
CIRCUMFERENTIAL	2 to 1	0.113	299.4	36.7	19.0	0.0
CIRCUMFERENTIAL	6 to 1	0.085	299.5	37.3	20.0	90.0
CIRCUMFERENTIAL	10 to 1	0.074	299.6	37.2	20.0	90.0
CIRCUMFERENTIAL	CONTINUOUS	0.068	299.6	37.1	20.0	90.0

FAVOR utilizes a PFM methodology that allows the vessel beltline region to be divided into major regions such as plates, axial welds, and circumferential welds. Each major region may be further subdivided into subregions, each of which may be assigned its own distinguishing parameters of: neutron fluence, copper, and nickel concentrations, RT_{NDTo}, flaw density, volume, flaw orientation and aspect ratio. A prototypical RPV beltline region in Figure 1 is divided into eleven weld regions.

The PFM analysis is based on Monte Carlo techniques, i.e. many deterministic analyses are performed on stochastically generated vessels to determine if each vessel, containing a specified number of flaws, will fail when subjected to a defined transient event (thermal-hydraulic boundary conditions) at a particular time in the operating life of the vessel. Each of the embrittlement-related parameters is sampled from a normal (Gaussian) distribution about the user-specified mean value. The conditional probability of failure for a specified PTS event is estimated by dividing the number of vessels that fail by the total number of vessels simulated. The term "failure" refers to full penetration of the vessel wall by a propagating flaw. The probability of failure is "conditional" in the sense that the transient is assumed to occur.

For purpose of illustration, a hypothetical embrittlement map for the eleven weld regions (shown in Figure 1) is specified in Table 2. The value of RT_{NDTs} is the value of RT_{NDT} at the inner surface of the vessel calculated according to Regulatory Guide 1.99 Revision 2. The value of RT_{NDTs} (2σ) is the value of $RT_{NDTs} + 2\sigma$, assuming a 2σ of 59°F. One of the axial welds (major region 4) in the intermediate shell is the most embrittled region. The value of RT_{NDTs} for this region is 211°F; therefore, the value of $RT_{NDTs} + 2\sigma$,= 270°F, which is the PTS screening criterion for an axial flaw. Therefore, for this plant to continue to operate, a plant-specific analysis, in accordance with Regulatory Guide 1.154 (U.S. Nuclear Regulatory Commission) would have to be performed.

Table 3 is one of the optional FAVOR output reports generated for a PFM analysis of 10^4 stochastically simulated vessels with the best-estimate embrittlement map specified in Table 2, assuming a flaw density of 1 flaw/m^3 (0.028 flaw/ft^3), subjected to the severe PTS benchmark transient. In this analysis, all flaws are assumed to be infinite length. Other PFM output reports may optionally be generated: (1) global PFM summary, (2) flaw size summary, (3) time histogram of failures, and (4) average values of key parameters.

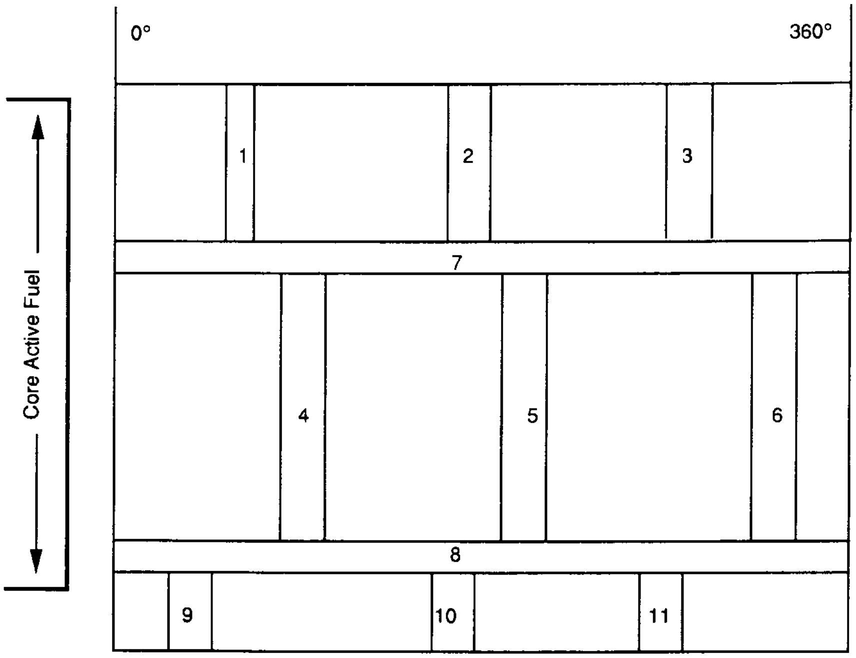

Figure 1. VESSEL BELTLINE LAYOUT

Table 2: Embrittlement map and flaw distribution used in PFM analysis of illustrative problem

Beltline region	Major region number	Chemistry Cu (wt %)	Chemistry NI (wt%)	Neutron fluence at inner surface 10^{19} n / cm^2	RT_{NDTo} (°F)	Region Volume (ft^3)	RT_{NDTs} (°F)	RT_{NDTs} (2σ) (°F)
upper axial weld	1	0.22	0.52	1.24	0	0.14	164	223
upper axial weld	2	0.22	0.53	0.82	0	0.14	147	206
upper axial weld	3	0.22	0.57	0.41	0	0.14	122	181
intermediate axial weld	4	0.22	0.57	3.15	0	1.06	211	270
intermediate axial weld	5	0.22	0.52	1.03	0	1.06	156	215
intermediate axial weld	6	0.22	0.54	2.07	0	1.06	189	248
circumferential weld	7	0.22	0.53	1.95	0	3.50	177	236
circumferential weld	8	0.22	0.52	1.27	0	3.50	186	245
lower axial weld	9	0.22	0.52	1.27	0	0.28	186	245
lower axial weld	10	0.22	0.53	1.64	0	0.28	165	224
lower axial weld	11	0.22	0.53	1.95	0	0.28	165	224

Table 3 : FAVOR PFM Major Region Summary

MAJOR REGION	RANK	REGION FLAWS	SIMULATED FLAWS	INITIAL INITIATIONS	ARRESTS TOTAL	ARRESTS STABLE	FAILED VESSELS	P(FIE)
4	1	0.030	2964	805	127	53	752	0.007520
6	2	0.030	2979	432	77	41	391	0.003910
11	3	0.008	757	87	16	7	80	0.000800
5	4	0.030	3010	100	28	22	78	0.000780
10	5	0.008	789	64	13	9	55	0.000550
9	6	0.008	842	37	11	7	30	0.000300
7	7	0.098	9688	506	553	491	15	0.000150
1	8	0.004	363	16	6	4	12	0.000120
2	9	0.004	384	9	5	4	5	0.000500
8	10	0.098	9857	207	215	207	0	0.000000
3	11	0.004	397	0	0	0	0	0.000000
Totals		0.32	32030	2263	1051	845	1418	.01418

The Major Region Summary contains a breakdown of the PFM analysis results by major regions, sorted (ranked) according to the contribution made to the total conditional probability of failure, designated as P(F|E). This summary includes the number of flaws in the region, number of simulated flaws, number of initial initiations, number of total and stable crack arrests, number of failed vessels, and P(F|E) by region. The number of flaws in each major region is determined by the summation of the products of the flaw densities and volume of all sub-regions in that major region.

6 VERIFICATION OF FAVOR SOLUTIONS

The FAVOR thermal, stresses, and K_I solutions have been verified to be within 1-2 percent of ADINA [Bathe, 1978] and ABAQUS three-dimensional finite element solutions. The FAVOR probabilistic solutions compared favorably with those generated by other codes during the NRC/EPRI PTS benchmarking exercise (Bishop, 1993); however, these problems did not examine some of the more difficult aspects of compliance with Regulatory Guide 1.154. The problems analyzed a single region of the vessel beltline assumed to have exactly one flaw, thus avoiding the issue of multiple vessel regions and multiple flaws. The problems also assumed that the vessel was unclad. The transients were assumed to be of simple stylized form rather than more complex transient definitions. Complex transient definitions, such as repressurizations, contributed most significantly to the frequency of vessel failure in the IPTS study. Future PTS benchmarking exercises should consider some of these more difficult issues.

7 SUMMARY

FAVOR provides the capability for very accurate descriptions of the thermal-hydraulic boundary conditions imposed on the inner-surface of the vessel wall, even for those complex transient definitions that exhibit discontinuities, such as pressure transients with repressurizations. FAVOR utilizes a PFM modeling methodology that allows the entire vessel beltline region (or any subset thereof), consisting of any number of sub-regions, each with its own specified fracture related characteristics and number of flaws, to be analyzed in a single PFM analysis. It is anticipated that FAVOR will continue to evolve such that the code continuously reflects the state-of-the art in pressure vessel fracture technology and complies with the current applicable regulatory criteria.

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