Department of Energy

Oak Ridge Operations Office
P.O. Box 2001
Oak Ridge, Tennessee 37831—

JUL 2 6 1996

Ms. Sue Decker
Office of Nuclear Regulatory Research
Financial Management, Procurement, and
Administrative Staff
U.S. Nuclear Regulatory Commission
Mail Stop T-10 D-5
Washington, D.C. 20555-0001

Dear Ms. Decker:

PROGRAM AND BUDGET PROPOSAL FOR FY 1996, "HEAVY SECTION STEEL TECHNOLOGY" (INTERAGENCY AGREEMENT DOE NO. 1886-N011-9B, JCN B0119)

Enclosed for your consideration is the Schedule 189 project proposal, subject as above, which has been prepared by the Oak Ridge National Laboratory (ORNL). This proposal is being submitted in response to an NRC Form 173, Order Number 60-96-471, dated June 27, 1996; NRC Form 173, Order Number 60-96-345, dated April 16, 1996; and NRC Form 173, Order Number 60-96-061, dated December 13, 1995.

Technical questions relative to this proposal should be directed to C. E. Pugh, ORNL Program Director, telephone (423) 574-0422. Administrative questions should be addressed to Darlene Cooper, DOE Work for Others Coordinator, telephone (423) 576-0646.

Sincerely,

Ronald O. Hultgren
ORNL Site Manager

ER-113:Cooper

DF03

Enclosure:
Schedule 189 (6)

cc w/o encl:
C. E. Pugh, Y-12, MS-8063
S. R. Martin, ORO, ER-111
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270017

96-112

Res Subj

NRC FORM 189 (Part 1)

(10-93)
NRCMD 11.7

U.S. NUCLEAR REGULATORY COMMISSION

DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK

DATE PROPOSAL SENT: JULY 19, 1996

	NEW	FY 1996
X	REVISION	NUMBER 1

PROJECT TITLE: HEAVY SECTION STEEL TECHNOLOGY

NRC OFFICE: U.S. NUCLEAR REGULATORY COMMISSION

DOE CONTRACTOR: Lockheed Martin Energy Research Corp.

SITE: Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831

JOB CODE: B0119

NRC B&R NUMBER: 66015114010

NRC BOC CODE: 253D

CONTRACTOR ACCOUNT NUMBER: 41 WO 11 9B 1

DOE B&R NUMBER: 40 10 01 06

PERIOD OF PERFORMANCE

PROJECT START DATE: 07/01/66

PROJECT END DATE: 12/31/98

[redacted]

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STAFF YEARS OF EFFORT		FY 1995	FY 1996	FY 1997	FY 1998	FY 1999
DIRECT SCIENTIFIC/TECHNICAL		9.3	10.3	8.0	7.5	4.1
OTHER DIRECT (SUPPORT SERVICES)		1.4	1.4	1.4	1.4	0.8
TOTAL DIRECT STAFF YEARS		10.7	11.7	9.4	8.9	4.9
COST PROPOSAL (Round to Nearest Thousand $)						
DIRECT LABOR (SCIENTIFIC/TECHNICAL)		1277	1156	922	964	533
OVERHEAD (INCLUDED IN DIRECT LABOR)						
MATERIALS/SERVICES		447	630	327	139	58
TRAVEL	FOREIGN	14	18	18	15	5
	DOMESTIC	43	53	53	47	14
SUBCONTRACT(S)		288	129	55	77	0
OTHER DIRECT						
GENERAL AND ADMINISTRATIVE EXPENSES		734	753	567	525	272
TOTAL ESTIMATED LABORATORY PROJECT COST		2803	2739	1942	1767	882
DOE ADDED FACTOR		121	118	84	76	38
TOTAL DOE PROJECT COST		2924	2857	2026	1843	920
CARRYOVER FROM PRIOR FY		1905	1626	709	483	440
CARRYOVER TO NEXT FY		1626	709	483	440	0
TOTAL FUNDING REQUIRED		2645	1940	1800	1800	480

NRC FORM 189 (Part 2)
(10-93)
NRCMD 11.7

U.S. NUCLEAR REGULATORY COMMISSION

DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK

JOB CODE: B0119

DATE: JULY 19, 1995

FOR PROJECTS, EXCLUDING TASK ORDERS AND TASK ORDER AGREEMENTS

PROJECT TITLE

HEAVY SECTION STEEL TECHNOLOGY

DOE PROPOSING ORGANIZATION

Lockheed Martin Energy Research Corp.
Oak Ridge National Laboratory

ESTIMATED COST BY TASK ($k)

TASK 1	TASK 2	TASK 3	TASK 4	TASK 5
2222	2873	2489	737	877
TASK 6	**TASK 7**	**TASK 8**	**TASK 9**	**TASK 10**
1021	3301			

The estimated task costs included DOE added factor costs. The costs include FY 1994 costs, and cover a period extending to the completion of the period of performance (12-31-98).

PROJECT DESCRIPTION

A NARRATIVE DESCRIPTION IS PROVIDED ON EACH OF THE FOLLOWING TOPICS IN THE ORDER LISTED.

1. OBJECTIVES OF PROPOSED WORK
2. SUMMARY OF PRIOR EFFORTS
3. WORK TO BE PERFORMED AND EXPECTED RESULTS
4. PROPOSED PERSONNEL — INCLUDE RESUMES
5. MEETINGS/TRAVEL
6. NRC FURNISHED MATERIALS
7. RELATIONSHIP TO OTHER PROJECTS
8. REPORTING REQUIREMENTS AND SCHEDULE
9. SUBCONTRACTOR/CONSULTANT AND MAJOR PROCUREMENT INFORMATION *
10. SPECIAL FACILITIES, IF REQUIRED
11. CONFLICT-OF-INTEREST INFORMATION
12. CLASSIFICATION OR SENSITIVITY, IF APPLICABLE (e.g., safeguards, proprietary, other)
13. ADDENDUM: (A) INTERPRETATIONS OF STATEMENT OF WORK, (B) COST INFORMATION, AND (C) SCHEDULE INFORMATION
14. SPENDING PLAN

* PROJECTS WITH COST-TYPE SUBCONTRACTS CANNOT BE CLOSED OUT UNTIL REQUIRED DCAA AUDITS HAVE BEEN CONDUCTED.

SIGNATURE — APPROVAL AUTHORITY	DATE
C. E. Pugh, Director, NRC Programs	

NRC FORM 189 (Continued) (10-93) NRCMD 11.7

U.S. NUCLEAR REGULATORY COMMISSION

DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK

JOB CODE: B0119

DATE: JULY 19, 1996

PROJECT TITLE: **Heavy Section Steel Technology**

1. OBJECTIVES OF PROPOSED WORK:

The objectives of the Heavy-Section Steel Technology (HSST) project are to:

A. Develop and experimentally validate the analysis methods needed to fully characterize the fracture behavior of heavy-section reactor pressure vessels (RPVs) and related components and structures under the full spectrum of loading and material conditions;

B. Develop the material property data, including appropriate test techniques and data-analysis methods needed in performing pressure vessel integrity analyses;

C. Assimilate the analysis methods, the materials data, and the pertinent service data into a comprehensive pressure vessel integrity assessment methodology that can be used by the Nuclear Regulatory Commission (NRC) in performing plant specific or generic pressure vessel safety analyses;

D. Reduce this technology to practice through participation in national and international codes and standards organizations; and

E. Provide technical assistance to the NRC in the general area of pressure vessel integrity.

2. SUMMARY OF PRIOR EFFORTS:

Fracture-margin-assessment methods were developed, and fracture toughness and crack-growth data were generated and transferred to the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. Crack-arrest testing technology was researched, and an American Society for Testing and Materials (ASTM) standard was developed. Elastic-plastic and dynamic-fracture analysis methods were developed and validated using large-scale, wide-plate tests. A viscoplastic fracture-analysis capability was assembled. Testing was performed to determine the effect of stainless steel cladding on the propagation of a fast-running crack. An extensive series of fracture technology verification tests was performed using heavy-section steel cylinders and pressure vessels fabricated using materials selected to simulate neutron-irradiation-embrittled reactor vessel materials. These tests provided data on crack-initiation and propagation behavior under pressure loading, thermal-shock loading, and pressurized-thermal-shock (PTS) loading. Many of the fracture technology issues currently under investigation were identified in these tests. Computer programs were developed for the fracture analysis of both laboratory specimens and reactor pressure vessels. Analysis methods for the assessment of reactor vessel failure probabilities during a PTS event were developed and incorporated into the Over-Cooling Accident-Probabilistic (OCA-P) and the Fracture Analysis of Vessels-Oak Ridge (FAVOR) computer programs. Stress-intensity-factor influence coefficients for infinite-length axial flaws were generated, verified, and incorporated into the FAVOR program. The FAVOR computer program was validated and issued to regulatory and nuclear industry users as a configuration-controlled program conforming with the ASME quality assurance requirements for nuclear applications 9ASME NQA-2-1989. Support was provided to the NRC for the evaluation of fracture-prevention margins in (a) the reactor vessel supports for the Trojan nuclear power station and (b) the reactor pressure vessel for the Yankee Rowe nuclear power station. Shallow-flaw and extended crack-arrest data were generated and their effect on reactor vessel PTS failure probabilities determined. A shallow-flaw fracture toughness database was assembled and used to assess the relative performance of candidate parameters for normalizing shallow-flaw fracture toughness data. Ductile-tearing technology problems were identified by participation in an international round-robin analysis of results from large-scale fracture experiments. Preliminary studies were completed on (a) the effect of reactor vessel dynamic response on crack arrest during a PTS event, (b) the effect of cladding on crack initiation and propagation, and (c) the effect of biaxial far-field-stress-states on crack initiation. These studies identified the need for fracture technology advances in the areas of crack-tip constraint effects and cladding effects. Development was initiated on dual-parameter, fracture toughness correlations. A cruciform test specimen was developed to provide an inexpensive means of investigating the effect of prototypical PTS biaxial-stress fields on the shallow-flaw fracture toughness of RPV steel. Test fixtures and a pilot series of cruciform test specimens were fabricated and tested. These tests confirmed that biaxial loading reduced the shallow-flaw fracture toughness of

pressure vessel steel under conditions of prototypical contained yielding. Analysis of the biaxial test specimen revealed that stress-based dual-parameter fracture toughness correlations could not predict the observed effects of biaxial loading on shallow-flaw fracture toughness. An implicit strain-based dual-parameter fracture toughness correlation was developed and shown capable of predicting the observed effects. Fractographic data were produced from these tests. The fractographic data support the use of strain as a controlling parameter for transition-range fracture toughness. A program of J-R curve testing of A302 Grade B pressure vessel steel was completed. An assessment was made of metallurgical effects which impact pressure vessel safe margin issues. An uncertainty evaluation of stress-intensity-factor estimates used in the ASME Code and regulatory documents was completed. Continuing membership of program personnel in the ASME and ASTM fracture technology working groups has assured prompt [illegible] of the program research products into the appropriate national consensus standards. These efforts have rece[illegible]ded significant contributions to the development of ASME Code criteria for evaluating vessel safety ma[illegible] low-upper-shelf conditions. Contributions were made toward the analytical verification and improveme[illegible]lly based equations for K_I due to steady-state-cooldown thermal loadings. Leadership was provided for the development of a draft ASTM standard for determining fracture toughness in the ductile-to-brittle transition temperature regime.

3. WORK TO BE PERFORMED AND EXPECTED RESULTS:

3.1 FY 1995

3.1.1 Program Management (Task 1)

Task 1 will provide overall management of the Heavy-Section Steel Technology (HSST) program to assure that the program objectives are achieved in a timely and cost-effective manner. Specific program management activities to be performed are as follows.

1. The program will be monitored and controlled using a cost/schedule variance analysis and management system. Program costs, financial status, and cost/schedule variances will be reported in monthly letter status reports (MLSRs). The MLSRs will report on progress at the Subtask level. The reports will include a description of the work performed and the progress made. Work performed by both the Oak Ridge National Laboratory (ORNL) HSST program research team and the program subcontractors will be reported in the MLSRs. The status of program deliverables such as NUREG/CR reports and letter reports will be reported. Any problems that impact the program cost/schedule performance will be identified. Action plans implemented to resolve the problems will be described and their effectiveness monitored and reported.
2. Program plans will be prepared in response to Statement of Work (SOW) issued by the NRC HSST Project Manager. Needs for subcontractor and consultant (S&C) support for specific elements of the SOW will be identified. S&C support will be used to make available to the program special facilities and talents not available at ORNL. S&C support may also be used to supplement capabilities available at ORNL.
3. SOWs will be prepared and subcontracts will be issued and administered for necessary S&C support.
4. Materials and components necessary for the efficient execution of the HSST program tasks will be located and procured.
5. A quality assurance program, tailored to the specific needs of the HSST program, will be used to assure high quality is maintained in reports and experimental data produced by the program.
6. Briefings on project activities and findings will be prepared and presented as directed by the NRC HSST Project Manager.
7. Coordinating services will be provided for both NRC and ORNL program and/or topical reviews.
8. Coordinating services will be provided for national and international information exchanges and technology transfers.
9. Liaison with the Heavy Section Steel Irradiation (HSSI) program will be maintained to assure coordination of the HSST and HSSI program activities.
10. The HSST Program Manager will coordinate the preparation and publication of semiannual reports covering all HSST program activities.

3.1.2 Constraint-Effects Analytical Development and Validation (Task 2)

The objectives of Task 2 are to assess, develop or refine, and apply as necessary, fracture analysis methods and validation tests to determine the influence of crack-tip constraint effects on fracture toughness. Results from this research will be used to improve the accuracy of RPV fracture predictions. This Task supports development of constraint-based methodologies to improve transferability of fracture toughness data (in the brittle-to-ductile transition temperature region) from small-scale (e.g., surveillance-sized) specimens to full-scale RPVs. It has been shown that out-of-plane loading induces crack-tip constraint effects on crack-tip driving forces as well as on the material fracture toughness as compared to toughness values determined under uniaxial loading conditions. This phenomenon was qualitatively verified during the FY 1994 performance period through the development-phase testing and analyses of intermediate-scale biaxial cruciform specimens with shallow flaws. For the performance periods FY 1995 through FY 1997, the work in this task will be focused on validation-phase testing and analysis to determine (a) the effects of biaxial loading ratios and test temperature on fracture toughness using a single flaw depth (single a/W ratio) and intermediate-scale cruciform specimens, (b) the effect of the combination of biaxiality and flaw depth on fracture toughness using the same configuration intermediate-scale cruciform specimens as in (a), and (c) verification of the transferability of the developed constraint methodology through testing of large-scale, biaxially loaded shallow-flaw specimens. To further support development of the basic constraint and fracture models, specialized, small-scale tests are also planned to investigate the effects of constraint on fracture ductility and the relationship between failure ductility, crack-tip-opening displacement (CTOD), and fracture toughness. Plane-strain tensile specimens, tensile fracture energy (CTOD) specimens, and slow-bend Charpy specimens will be used as appropriate for this purpose. The intermediate- and large-scale cruciform beam and small-scale specimen testing focuses on the behavior of RPV material in the brittle-to-ductile transition temperature region of the fracture toughness curve.

To provide the micromechanical process definitions necessary for a complete description of the fracture processes in the transition temperature region and to fully support the development and verification of dual-parameter fracture toughness methodologies, interface with the ORNL HSSI Program will be maintained. Using broken biaxial test specimens, guidance will be obtained on (a) interpretation of the fracture process by investigation of the fracture surfaces, (b) location of fracture initiation sites, and (c) amounts of ductile tearing before cleavage. The information will be obtained by reconstruction of the fracture process using confocal mapping and by direct examination and cross-sectioning of the fracture surfaces to make measurements of the plastic zone size and the crack tip radius near the cleavage initiation site.

Task 2 is divided into two Subtasks. The first Subtask will develop the experimental base required to define and quantify biaxial loading effects on constraint. The second Subtask will investigate and evaluate existing dual-parameter methodologies, or recommend alternative methodologies if appropriate, for predictions of fracture in the transition temperature region of the fracture toughness curve. International information exchange in the areas of constraint and large scale testing will be supported through this and other tasks. The Subtasks and the specific activities to be performed in FY 1995 are summarized below.

3.1.2.1 Biaxial-Loading-Effects Validation Testing (Subtask 2.1). This Subtask investigates the influence of biaxial loading on the shallow-flaw fracture toughness of RPV material. Uniaxial shallow-flaw toughness exhibits an increase in scatter and mean value relative to deep-flaw toughness data. In comparison, based on the development-phase cruciform testing, biaxial shallow-flaw toughness exhibits a decrease in both mean value and scatter relative to the uniaxial shallow-flaw results, but the mean value does not appear to be less than that for uniaxial deep-flaw data. This biaxial-loading toughness reduction will be quantified using shallow-flaw cruciform specimens fabricated from RPV material. The primary focus of this Subtask for this performance period will be the verification of the biaxial loading effects on shallow-flaw fracture toughness at representative temperatures and flaw depths for RPV analysis. This Subtask is an extension of the development phase of the biaxial-loading-effects task conducted during the previous performance period. Testing and analysis will thus take advantage of previous experience wherever possible. The flaws under consideration in this Subtask are constant-depth two-dimensional (2-D) flaws.

3.1.2.1.1 Verification-Phase Testing (Subtask 2.1.1) Cruciform testing will be performed in the transition region of the fracture toughness curve at temperatures selected to cover the lower- to mid-transition range. A total of 16 tests is proposed for the verification testing. The test proposed test matrix is given in Table 2.1. A total of 16 tests is proposed for the verification testing. The test matrix is grouped into two phases for definition of test biaxiality ratios. Phase I includes a series of six specimens tested under 0:1, 0.6:1, and 1:1 biaxiality ratios. Results from these tests will be used to define the baseline and the most severe condition for the tests to be performed in Phase II. The majority of these tests will be conducted at temperatures such that the failure mode is predominately cleavage with some prior ductile tearing that is prototypic of RPV behavior. The source material for these tests will be HSST Plate 14. This material will be used in a heat treated condition to permit full evaluation of biaxial effects, i.e., heat-treated to elevate the yield and ultimate stress and simulate radiation-damaged properties. Material characterization of Plate 14 in the heat treated condition will be conducted as a part of this Subtask. Fractographic information will be obtained for a number of the tests. Location of initiation sites, the amount of ductile tearing, the crack-tip radius, and the extent of the plastic zone size developed around the flaw tip will be determined.

Table 2.1 Proposed Test Matrix for Biaxial Loading Effects Verification Testing (Subtask 2.1.1)

Batch #	Normalized Test Temperature	Load Biaxiality Ratio	Notes
Phase I			
1	TBD	0:1	
2	TBD	0.6:1	a
3	TBD	1:1	
Phase II			
4	TBD	0:1	b
5	TBD	0.6:1 or 1:1	c
6	TBD+ 20°C	0:1	d
7	TBD+ 20°C	0.6:1 or 1:1	a
8	TBD- 30°C	0.6:1 or 1:1	a, d

Test Specific Notes:

a. **Batches 2 and 3 will determine the more severe biaxial ratio. That ratio (0.6:1 or 1:1) will be used for Batches 5, 7, and 8.**

b. **Batch 4 is identical to Batch 1 to provide a baseline for assessing the impact of biaxial loading on toughness scatter**

c. **Batch 5 will be identical to either Batch 2 or 3 and will be used with Batches 1 and 4 to assess the impact of biaxial loading on scatter.**

d. **Three test temperatures in the transition region will be sampled to determined the biaxial-loading effect in terms of temperature shift.**

General Notes:

e. **All tests will be conducted with the cruciform specimen configuration developed during FY 1993-94 using a 2-D flaw with an a/W ratio of 0.1.**

f. **All specimens will be tested in a heat-treated condition to assure prototypic stress-strain response.**

g. **A batch refers to two specimens tested at identical conditions. A total of 16 specimens or 8 batches are specified for this matrix.**

h. **Test temperatures are to be determined (TBD) based on characterization of test material.**

i. **Load ratio is denoted as transverse:longitudinal load. 0:1 is uniaxial loading and 1:1 is equibiaxial loading.**

Specimen fabrication will be initiated and completed in the FY 1996 performance period. Testing will be completed in the FY 1996 performance period. The specimen design will be essentially the same as that used in the development testing performed in FY 1994. A test section nominally 4-in. thick with a constant depth (a/W = 0.1) flaw will be used. The development tests demonstrated that the failure loads required for tests performed at temperatures below the nil-ductility temperature (NDT) required loads near the upper limit of the capacity of the servo-hydraulic test machine being used (550-kip INSTRON). Since it is proposed that testing be performed at temperatures above NDT, the capacity of the servo-hydraulic test machine will be upgraded from the current 550-kip to near 700-kip by replacing the control system and the servo-valve, and adding a new computer control unit recalibrating to the stall-capacity of the servo-hydraulic system. The test machine manufacturer has been consulted and has prepared a proposal and quote for this work.

3.1.2.1.2 Analysis of the Test Data (Subtask 2.1.2) Analysis of the test data will be performed to determine the toughness from the data provided in Subtask 2.1.1. Analysis will be conducted to estimate the load vs crack-mouth-opening-displacement (P-CMOD) η-factors required to interpret the test data as a function of crack depth, temperature, and load ratio. Material properties for the analytical model will be determined in Subtask 2.1.1. Both pre- and post-test analysis will be performed to guide the test effort and to provide comparisons between computed and measured mechanical response. Assessment of post-test comparisons will be used to identify any necessary refinements or modifications to the modeling procedures to assure accurate predictions of specimen deformation and, ultimately, fracture toughness estimates. Refined crack-tip modeling will be conducted as a part of Subtask 2.2.

At the completion of Phase I testing, a letter report providing test results, analysis results, and conclusions for the effect of biaxiality on toughness will be issued. Preliminary fractographic results related to initiation-site location and plastic-zone-size determinations will be included. This letter report will be issued within thirty days of completion of the Phase I tests and is planned for mid-FY 1996.

A second letter report detailing the test and analysis results for all specimens in this matrix, (Phase I and Phase II), will also be issued. The report will include test results, analysis results, test and analysis comparisons, η-factors used to determine toughness from the test data, summarized fractographic results, and interpretation of the toughness results. The interpretation will include a quantification of the fracture toughness reduction due to biaxial loading and an assessment of the influence of biaxial loading on the scatter of fracture toughness results. Special attention will be given to the effect of constitutive modeling in the predictions of toughness values and suitable comparisons will be made between measured and computed mechanical responses. Detailed analyses will also be performed on the small-scale specimen types tested under Subtask 2.1.1. Stress and strain limits and strain-energy at failure will be determined, and a preliminary evaluation of pretest predictions will be included in the letter report.

3.1.2.2 Constraint Effects Correlation Development and Verification, (Subtask 2.2) An assessment initiated in FY 1994 demonstrated that existing stress-based dual-parameter fracture methodologies, i.e., the J-Q methodology combined with Ritchie-Knott-Rice fracture criteria and the Dodds-Anderson constraint-adjustment technique, do not predict the effects of biaxial loading on fracture toughness in the transition temperature region. An alternative strain-based dual-parameter methodology was proposed and received preliminary validation using the limited amount of biaxial data generated under the development phase of the biaxial-loading-effects investigation. In FY 1995, this Subtask will continue development and assessment of the strain-based methodology. To assure achievement of a fully validated constraint-effects fracture methodology, support will also be continued for the modification and verification of the existing stress-based methodologies to determine the limits of their applicability. Generalization of the Dodds-Anderson toughness scaling model to include plastic strain (see Task 4) will be included in this activity. To evaluate the various fracture methodologies, detailed, near-crack-tip finite-element fracture mechanics analyses will be performed of (a) the cruciform specimens previously tested under the loading effects development phase of the program, (b) those being tested in the validation phase of Subtask 2.1 above, (c) the full-thickness clad beam specimens tested under Subtask 3.3, and (d) the clad cruciform beams being tested under Subtask 3.4. Alternative constraint methodologies will be investigated, as appropriate, for feasibility of their potential development and validation. Correlation of crack initiation sites from fractographic

data with relevant near-crack-tip fields will provide an important criterion for evaluating the applicability of the various fracture models. A preliminary assessment of dual-parameter fracture methodologies will be completed in this performance period.

Initial results from this evaluation will be included in an interpretative NUREG/CR report which will be prepared on completion of this effort. The report will describe the effects of crack-tip constraint on the fracture behavior of uniaxially and biaxially loaded specimens at temperatures in the transition range. The report will include the evaluation of both the stress- and strain-based fracture methodologies that was started in FY 1994. The report will include comparisons of fracture predictions with data from shallow-crack beams tested (uniaxial and biaxial) by ORNL, from shallow-crack beams tested (uniaxial) by the U. S. Naval Surface Warfare Center (NSWC), from full-thickness clad beams tested under Subtask 3.3 [tested at the National Institute for Standards and Technologies (NIST) under subcontract to ORNL], and from biaxial clad beams tested under Subtasks 3.4. This report will include a recommendation as to which fracture methodology (stress and/or strain/ductility based) appears to have the most promise for improving the accuracy of RPV fracture assessment. This report will be completed by mid-FY 1996.

Metallurgical examinations will be made of fracture surfaces from shallow-flaw fracture toughness specimens tested under uniaxial and biaxial loading. The fracture-initiation-site information will be used by ORNL, together with elastic-plastic analysis of the crack-tip stress-strain field, to determine if crack initiation occurred in a location where the opening-mode stress was increasing with increasing applied load. This information will be used in the evaluation of stress-based dual-parameter fracture toughness correlations. Sections cut at 90° to the fracture surface will be etched to reveal the size and configuration of the crack-tip plastic zone. This information will be used to validate and further develop a strain-based dual-parameter fracture toughness correlation.

3.1.3 Evaluation of Cladding Effects (Task 3)

Objectives for this Task are to provide the following: (1) a quantitative description of cladding effects on the fracture behavior of shallow finite-length surface cracks in RPVs and (2) a basis for improved treatment of surface-crack geometries in fracture-assessment procedures applied to PTS and pressure–temperature (P–T) limit transients.

The impact of cladding effects on RPV safety-margin assessments are not well understood. Current PTS analysis computer codes recognize the influence of the inner-surface cladding layer in the heat transfer and stress analysis models but assume the cladding fracture toughness to be the same as that for the base material. These codes do not recognize the influence cladding may have in inhibiting crack initiation and propagation from shallow surface flaws of finite length. Limited experimental data and analyses indicate that cladding can inhibit the initiation and propagation of certain finite-length shallow flaws. First, the high fracture toughness of irradiated stainless steel cladding can inhibit tearing of that portion of a surface crack located within the cladding. Second, the low yield stress of the cladding acts to reduce the stress intensity factor on portions of the crack front located within the base metal for a shallow finite-length crack that penetrates the cladding.

Within this Task, analytical studies and validation testing will be performed to resolve cladding issues and to refine safety-assessment procedures. The work will focus on the following:

1. A quantitative description will be developed for the effects of cladding on the fracture behavior of surface cracks (with small depths and lengths) in RPVs subjected to overcooling transients. This will involve laboratory-scale clad cruciform specimens tested uniaxially and biaxially, representing typical crack-tip loading conditions for RPVs. It will also involve participating in international cooperative efforts to predict the results of clad RPV tests already performed or in progress.
2. A methodology will be developed for including cladding effects in current RPV integrity assessment procedures. This will provide a basis for introducing an improved treatment of surface-crack initial geometries in fracture assessment procedures applied to PTS and P–T limit transients.

Interactions will be maintained with the HSSI Program to provide an interpretation of the fracture process by investigating crack surface reconstruction of the broken test specimens (shallow-flaw specimens under uniaxial and biaxial loading), using confocal mapping.

Task H.3 is divided into six Subtasks that are concerned with closely related aspects of the cladding effects issue. The six Subtasks and the specific accomplishments planned for each Subtask in FY 1995 are described below.

3.1.3.1 Quasi-Static Clad-Yielding-Model Development (Subtask 3.1) This Subtask is concerned with the formulation and validation of a clad-yielding model that can be incorporated into linear-elastic fracture mechanics (LEFM) influence-coefficient methodology. Conventional practice in assessments of RPVs assumes a thermoelastic constitutive model and base-metal fracture toughness properties for the discrete cladding region. However, crack-initiation studies indicate that incorporation of clad yielding into the assessment models reduces the strain controlled element of the crack driving forces for shallow flaws. Also, ductile fracture toughness of cladding may prevent longitudinal propagation of many finite-length shallow flaws. These studies imply that fracture-assessment procedures may be significantly improved when clad mechanical and fracture toughness properties, including the effects of radiation, are incorporated into the calculations.

Influence-coefficient methodology based on LEFM concepts is generally used to perform deterministic and probabilistic RPV assessments. This methodology is employed in the ORNL-developed FAVOR probabilistic fracture mechanics (PFM) code. As a near-term refinement in the assessment methodology, the development and validation of the generic clad yielding model started during the FY 1994 work period will be completed during the FY 1995 work period. The generic model will incorporate the clad yielding into the calculations, while permitting the LEFM influence coefficient approach to be retained in the presence of the cladding nonlinear response. The generic clad yielding model will be implemented in the FAVOR PFM code. Validation of the model predictions will be done with available test data and analyses. A letter report on the model development that was started during the FY 1994 work period will be issued by the end of the FY 1995 work period. The letter report will include any empirical equations defining the model, validations performed to evaluate model, and limitations of the clad yielding model.

Specific accomplishments planned for this Subtask in the FY 1995 performance period are as follows:

- complete development of a generic clad-yielding model, started during FY 1994, for incorporation into the LEFM influence-coefficient methodology,
- complete a matrix of analytical solutions for clad vessel cases that will define the generic clad-yielding model,
- complete implementation of generic model in FAVOR code,
- complete validation of the generic clad-yielding model using available test data, and
- issue a letter report on development and validation of the clad-yielding model.

3.1.3.2 Cladding Method Development (Subtask 3.2) This Subtask will develop a materials characterization data base for the standardized nuclear-unit-power-plant system (SNUPPS) shell material that meets testing requirements described in Subtasks 3.4 and 3.5. Testing of the SNUPPS material will focus on the "as received" condition (i.e., no heat treatment). Development of the data base for the SNUPPS material is necessary for the selection of crucial test parameters (eg., test temperature) and for the analysis of computational models of the tests. Also, it is essential to establish that the SNUPPS cladding exhibits ductile behavior and a yield stress representative of irradiated conditions near the plate nil-ductility temperature (NDT). [Previous HSST analyses indicated that clad tearing should not be an issue for shallow flaws (a<0.7 in.) in irradiated RPVs subjected to severe PTS transients. Therefore, should the SNUPPS cladding have a relatively high toughness, this factor would not impact objectives of Task 3].

Tensile, Charpy, plane-strain ductility, and drop-weight testing will be performed to establish NDT and the transition temperature of the SNUPPS weld and plate material. Sheet-type plane-strain tensile specimens taken from the clad region and the cladding heat-affected zone (HAZ) will be tested near NDT of the material. A letter report will be issued that describes the results of the materials-characterization studies.

Specific accomplishments planned for this Subtask in the FY 1995 performance period are as follows:

- complete tensile, plane-strain ductility, Charpy, and drop-weight tests for determination of material properties, NDT and reference transition temperature for SNUPPS material,
- complete tests of sheet-type tensile specimens from cladding and HAZ of SNUPPS material, and
- issue a letter report on development of the characterization of the SNUPPS material.

3.1.3.3 Uniaxial Full-Thickness Clad Beam Testing and Analysis (Subtask 3.3). This Subtask is concerned with testing and analysis of uniaxial large-scale clad beam specimens fabricated from material removed from the wall of a surplus commercial RPV. During the FY 1994 work period, a series of full-thickness clad beam specimens with a through-width shallow crack were tested under three-point bending at NIST, under sub-contract to ORNL, to determine the effect of shallow flaws on fracture toughness of prototypic reactor materials (weld and base metal) in the transition temperature region. The initial series of tests had the crack located in weld material. During the FY 1995 work period, the remaining three tests from the test-matrix proposed in the FY 1994 Form 189 will be completed. These tests will have the crack located in plate material. Also, post-test finite element analyses of the near-crack-tip region of the test specimens will be performed. A NUREG report is to be prepared during the FY 1995 work period, giving the results of the testing and analyses performed under this Subtask. Influence of metallurgical inhomogeneities and the cladding process on fracture toughness of the material will also be addressed. These results will be provided to Subtask 2.2 on constraint-effects correlation development and verification.

Specific accomplishments planned for this Subtask in the FY 1995 performance period are as follows:

- complete testing by NIST of three full-thickness clad beams provided by ORNL (to be performed under existing Interagency Agreement with NIST, DE-AI05-92OR22034, extending through April 30, 1995),
- complete posttest finite-element analyses of near-crack-tip region in full-thickness clad beams tested at NIST,
- complete evaluation of the influence of metallurgical inhomogeneities and cladding process on fracture toughness of material, and
- issue a NUREG report on testing and analysis of full-thickness clad beams.

3.1.3.4 Biaxial Clad Cruciform Specimen Testing and Analysis (Subtask 3.4). Analysis and testing of clad cruciform specimens containing finite-length shallow surface cracks will be performed under this task. These "intermediate-scale" clad-specimen tests are needed to generate significant amounts of test data to understand the behavior of flaws in RPVs with test conditions as close to prototypic as possible. Ductile deformation and failure processes are known to be sensitive to the biaxial stress fields (i.e., axial/circumferential in a cylindrical vessel) that are imposed on an RPV wall by pressure and thermal loading conditions. Testing of clad cruciform specimens under biaxial loading provides a mechanism for approximating the effects of those stress fields on shallow through-clad surface cracks.

Item 3.4.1: Analyses initiated during the FY 1994 work period will be completed for typical pressurized water reactor (PWR) RPVs to predict an envelope of finite flaw sizes (depths and lengths) and PTS loadings that would not result in initiation and growth into long, 2-D flaws. These analyses will include the predicted effects of loss of crack-tip constraint on fracture toughness. A letter report on the results obtained for the envelope in terms of flaw sizes and loading conditions will be issued during the performance period prior to initiating testing of specimens for purposes of verifying this envelope.

A three-dimensional (3-D) elastic-plastic finite element model of a finite-length surface-flaw in a RPV will be generated. The model will be used to define the crack-tip stress and strain fields under PTS transient loading. Results from this analysis will be used, together with results from the ORNL analysis of the cruciform specimen, to determine the transferability of results from both stress-based and strain-based dual-parameter fracture toughness correlations. A letter report will be issued upon completion of the analyses in FY 1995.

Item 3.4.2: This item addresses a testing program using clad cruciform specimens to validate the analyses described in Item 3.4.1 above. The work under this item includes defining a matrix of verification tests to investigate and qualify the limits of the envelope developed in Item 3.4.1 using clad cruciform specimens with finite-length, shallow surface flaws. The cruciform specimens used in prior testing have the essential features of PTS biaxial stress fields and offer the potential for determining both the distribution and scatter of initiation conditions.

Clad cruciform specimens will be fabricated from clad-weld-plate material taken from the SNUPPS shell section at ORNL. The weld-overlay cladding from the SNUPPS shell segment will be retained in the test section of the cruciform specimens. These test sections will be fabricated from the SNUPPS clad-weld material in the "as received" condition to take advantage of the relatively high yield stress properties (approximately 87 ksi at room temperature) of the weld material. The cladding included in the test section must exhibit ductile behavior at the test temperature, but tearing toughness of the cladding is not regarded as an issue in achieving the objectives of the testing program.

This Subtask will fabricate the required specimens, develop procedures for conducting the tests, perform the tests, and report the test results. (Procedures used for these clad-cruciform tests will be essentially the same as those used for the unclad cruciform specimens tested under Subtask 2.1; necessary modifications required by the presence of the cladding will be determined from development tests.) These test data are expected to provide initial results leading to verification of the analytical procedures used to define the envelope of non-initiating flaw sizes and loading conditions.

Pretest and posttest computational analyses of the clad cruciform specimens will be made and interpretation of the test results will be carried out. Also, finite-element analyses of the near-crack-tip region of the test specimens will be performed. A letter report will be issued by the end of performance period describing progress in the testing and analysis of clad cruciform specimens. The results obtained in this Subtask on testing and analysis will be provided to Subtask 2.2 for developing-constraint effects correlations and verification.

During the FY 1995 performance period, six development clad cruciform specimens will be fabricated from SNUPPS clad-weld material in the "as received" condition. The development clad specimens will contain finite-length surface cracks with the same dimensions as the unclad specimens of Subtask 2.1 ($a = 0.8$ in.; $2c = 2.1$ in.). Testing will take place at the NDT of the SNUPPS material. These specimens will be tested in uniaxial and biaxial loading (three each) to develop test procedures and to identify critical test parameters and instrumentation requirements (e.g., required instrumentation for measuring crack-mouth-opening displacements for through-clad cracks).

Following completion of the development phase, a series of clad cruciform specimens will be tested in two phases from the verification test matrix given in Table 3.1. In the FY 1995 performance period, two clad cruciform specimens (group 1 of Phase I) will be tested at the transition temperature and loading conditions indicated in Table 3.1. (A group refers to two identical specimens tested under the same conditions.) Testing of groups 2-3 in Phase I and groups 4-9 in Phase II is scheduled to be completed during the FY 1996 performance period.

Groups 1 and 2 in Table 3.1 replicate the test conditions (crack geometry, temperature, and loading) of the development phase.

The Phase I tests (i.e., the first series of six specimens) will provide a data set that can serve as a reference in the transition temperature region for a particular set of conditions summarized in Table ?.1. These results should provide guidance for further investigation of variables associated with cladding effects on crack initiation and propagation that are scheduled for the FY 1996 and 1997 performance periods (i.e., in Phase II and in testing of large-scale specimens under Subtask 3.5).

Specific accomplishments planned for this Subtask in the FY 1995 performance period are as follows:

- complete analyses of typical PWR-RPVs to predict a non-initiating envelope of finite sized flaws and PTS loadings,
- issue letter report on non-initiating envelope of flaw sizes and loading conditions,
- complete analyses to determine transferability of dual-parameter correlations to RPV assessments,
- issue letter report on transferability of dual-parameter correlations,
- complete fabrication of six surface-cracked clad cruciform specimens for development testing,
- complete development testing of six clad cruciform specimens,
- complete development of procedures (including flaw sharpening) and instrumentation for conducting tests of clad cruciform specimens,
- complete fabrication of group 1 surface-cracked clad cruciform specimens for initiation of Phase I verification testing,
- complete tests of group 1 clad cruciform specimens in Phase I verification testing,
- complete computational analyses of group 1 clad cruciform specimens, and
- issue letter report describing testing and analysis of clad cruciform specimens.

3.1.3.5 Large-Scale Clad Cruciform Specimen Testing and Analysis (Subtask 3.5). The objective of this Subtask is to study the most prototypic specimen, less than a clad cylinder, to assess cladding effects. Using limited intermediate-scale specimens, it has been shown both experimentally and analytically that a tensile, out-of-plane, biaxial stress reduces fracture toughness below the value in uniaxial loading of the same specimen. Preparations for a series of large-scale clad cruciform-specimen tests to investigate the influence of cladding, flaw depths, and biaxial-loading ratios on fracture toughness will be initiated during the FY 1995 performance period. Large-scale cruciform specimens allow these factors to be studied under prototypic biaxial conditions while circumventing some difficulties associated with transfer of fracture toughness data from smaller laboratory-scale specimens to full-scale structures. This Subtask will define the tests to be performed, monitor the progress of tests, and report test results. Pretest finite-element analysis of the specimen will be performed with appropriate near-crack-tip mesh refinement.

Clad cruciform specimens will be fabricated from the SNUPPS shell material in the "as received" condition. The test section of the specimen will contain a through-clad surface flaw located in clad-weld material. Once the specimens have been prepared, a readiness review will be conducted prior to any testing. Post-test finite-element near-crack-tip analyses of the specimens and correlations will be performed with the selected constraint-effects model (from Subtask 2.2).

A preliminary test matrix for the large-scale testing program is provided in Table 3.2. Testing of large-scale clad cruciform specimens will commence at the test facility during the FY 1996 performance period and will be completed during the FY 1997 performance period. Selection of test parameters will be strongly influenced by results from the intermediate-scale testing program conducted under Subtask 3.4.

During the FY 1995 performance period, the servo-hydraulic test machine employed by the HSST program at ORNL will be upgraded to increase the total load capacity available. The modification will involve replacement of the control system and servo valve, addition of a computer control unit, and recalibration of the loading system to increase the overall machine capacity from 550 kips to a maximum of 700 kips. This system upgrade will be performed in connection with Subtask 2.1. In conjunction with the test machine upgrade, a new biaxial test fixture will be designed and fabricated. This new fixture will be designed to the load limit of the upgraded test machine and will have provisions for accommodating larger cruciform beams. The same principles of operation will be retained as are used for the existing test fixture. A fitness demonstration will be completed for the new test facility, and the required test procedures will be developed using a dummy large-scale cruciform specimen fabricated for that purpose. A letter report will be issued by the end of the performance period describing progress in the large-scale clad cruciform testing program.

Table 3.1. Matrix of Verification Tests of Clad-Cruciform Specimens with Shallow Surface Flaws

- All tests will be conducted with a cruciform specimen of 102-mm (4 in.) thickness inclusive of cladding. Crack depths are measured from the clad surface. Nominal cladding thickness will be 4 mm (0.16 in.).
- All specimens will be tested with the base metal in the heat-treated condition to simulate radiation- damaged material.
- A group refers to two identical specimens tested under the same conditions. A total of 18 specimens or 9 groups are specified in two phases for this matrix.
- Test temperatures are specified in terms of NDT. Actual temperatures will be determined once NDT is known for the heat-treated material.

Group #	Crack Geometry Depth (in.)	Crack Geometry Length (in.)	Normalized Test Temperature	PT : PL	Notes
Phase I					
1	0.6	1.5	NDT	0:1	a
2	"	"	NDT	0.6:1 or 1:1	a
3	"	"	NDT -30°C	0.6:1 or 1:1	
Phase II					
4	0.6	1.5	NDT +20°C	0:1	
5	"	"	NDT +20°C	0.6:1 or 1:1	
6	Variable		NDT	Biaxial	b, c
7			NDT	"	
8	"	"	NDT +20°C	"	
9	"	"	NDT +20°C	"	

Notes:

a These initial two groups utilize the same crack geometry, temperatures, and loading conditions defined in Table 2.2 of Subtask 2.3.

b Crack geometry and loading conditions for testing of groups 6–9 will be selected after sufficient data becomes available from groups 1–5.

c Dependent upon result of groups 1–5.

During the FY 1995 performance period, the servo-hydraulic test machine employed by the HSST program at ORNL will be upgraded to increase the total load capacity available. The modification will involve replacement of the control system and servo valve, addition of a computer control unit, and recalibration of the loading system to increase the overall machine capacity from 550 kips to a maximum of 700 kips. This system upgrade will be performed in connection with Subtask 2.1. In conjunction with the test machine upgrade, a new biaxial test fixture will be designed and fabricated. This new fixture will be designed to the load limit of the upgraded test machine and will have provisions for accommodating larger cruciform beams. The same principles of operation will be retained as are used for the existing test fixture. A fitness demonstration will be completed for the new test facility, and the required test procedures will be developed using a dummy large-scale cruciform specimen fabricated for that purpose. A letter report will be issued by the end of the performance period describing progress in the large-scale clad cruciform testing program.

Table 3.2. Test Matrix for Large-Scale Clad-Cruciform Testing Program

Specimen No.	Test objective	Normalized Test temperature
1	Demonstration of fracture for finite-length crack selected on basis of small-cruciform-specimen tests (Subtask 3.4).	NDT
2	Demonstration of no fracture up to limit load for finite-length crack selected on basis of small-cruciform-specimen tests (Subtask 3.4).	NDT
3	Repetition of test 1	NDT −30°C
4	Repetition of test 2	NDT −30°C

Specific accomplishments planned for this Subtask in the FY 1995 performance period are as follows:

- complete modifications and testing of INSTRON machine at ORNL for increased loading capacity,
- complete design and prepare engineering drawings approved for construction by ORNL, for fabrication of a specimen and test fixture for large-scale clad cruciform fracture-toughness testing,
- complete pretest finite-element analysis of specimen model incorporating appropriate near-crack-tip mesh refinement, and
- complete procurement of hardware for fabrication of the test fixture for the large-scale clad cruciform testing.

3.1.3.6 Validation Through International Participation (Subtask 3.6) The objective of this Subtask is to validate RPV fracture-analysis methods through applications to experimental data from model clad-unclad vessels and test specimens. This is accomplished through participation in round-robin analysis activities of the Fracture Assessment Group (FAG) of Organization for Economic Cooperation and Development/Nuclear Energy Agency's Committee on the Safety of Nuclear Installations/Principal Working Group No. 3 (CSNI/PWG-3). Emphasis will be placed on Phase II of the Project for the Fracture Analysis of Large-Scale International Reference Experiments (FALSIRE II), which is sponsored by CSNI/FAG. This Subtask provides input to another ORNL project, "RPV International Program Support," under Job Code B5703.

During the FY 1995 performance period, an assessment will be made of analysis results from the FY 1994 FALSIRE II Workshop that will focus on near-crack-tip stress and strain fields. These local crack-tip fields represent required input to stress-based and strain-based correlation models that quantify effects of constraint on fracture toughness. The purpose of this assessment is to determine the extent to which these results provide additional validation of the constraint-effects methodology being developed under Subtask 2.2.

(These FALSIRE II analyses are based on detailed problem statements for six reference experiments prepared by the CSNI/FAG during the FY 1993 and FY 1994 performance periods). A letter report will be issued during the FY 1995 performance period immediately following completion of this assessment. Activities under this Subtask include HSST participation in the 13th International Conference on Structural Mechanics in Reactor Technology (SMiRT-13) to be held in Porto Alegre, Brazil, during August 13–18, 1995. Presentations of three technical papers describing research performed under Tasks 3, 4, and 5 will be prepared and presented at the SMiRT-13 Conference. (Titles of the three papers were submitted to the NRC during the FY 1994 performance period). A foreign trip report describing HSST staff participation in SMiRT-13 will be issued two weeks after completion of the c ference.

Specific accomplishments planned for this Subtask in the FY 1995 performance period are as follows:

- complete assessment of FALSIRE II analyses to provide additional validation of constraint-effects methodology being developed under Subtask 2.2,
- issue letter report describing contribution of FALSIRE II analysis results to validation of HSST constraint effects methodology,
- prepare three presentations for SMiRT–13 describing HSST program research,
- participate in SMiRT–13 conference, and
- issue foreign trip report on HSST participation in SMiRT–13 conference

<u>3.1.4 Ductile-To-Cleavage Fracture-Mode Conversion (Task 4)</u>

In the lower-to-upper transition regions of fracture toughness versus temperature behavior, RPV materials can exhibit considerable ductile flaw growth followed by a fracture-mode conversion to cleavage. The material failure by cleavage after some amount of ductile tearing can be regarded as a combined effect of a deterministic stable-tearing process (J-R curve) and a probabilistic cleavage process. Analytical models exist that predict that ductile tearing in advance of cleavage acts to decrease the crack-tip radius of a previously blunted crack tip. Ignoring the presence of significant amounts of pre-cleavage ductile tearing may lead to reduced accuracy in predicting cleavage initiation and resulting margins of safety. The objective for this task is the characterization and development of an engineering model to take into account any pre-cleavage ductile tearing in fracture predictions for RPVs. The fracture-mode-conversion model is needed to provide a comprehensive fracture-prediction methodology to assess accuracy of computed RPV fracture margins. The technical approach employed to develop and validate a fracture model for predicting mode conversion in the transition temperature region is outlined as follows:

1. Obtain fracture and tearing toughness data from shallow-flaw SENB and cruciform specimens.
2. Use toughness data to test stress- and strain-based dual parameter fracture-toughness correlations for cleavage initiation.
3. Develop cleavage initiation model by performance trial: (a) stress-based dual parameter fracture-toughness correlations (J-Q, J-A_{cr}); (b) strain-based dual parameter fracture toughness correlations [K_{Jc}-ln(R)]; and (c) modified stress-plastic strain fracture toughness correlation[J-$A_{cr}(\epsilon_{pl})$].
4. Define form(s) of the cleavage-fracture model(s) to be used in the ductile tearing-to-cleavage mode-conversion model.
5. Develop ductile tearing model which will : (a) reproduce J_R-curve test data; (b) require only input data that are validated and readily available; and (c) provide output that includes crack-tip radius and crack-plane plastic zone width as a function of crack growth.
6. Obtain relevant data (fractography and micromechanical features) for the calibration and practical applicatio of the ductile tearing models.

The task is divided into the following three Subtasks:

<u>3.1.4.1 Metallurgical Investigations (Subtask 4.1)</u> Under this Subtask, metallurgical investigations of existing test results are underway. The objective for these investigations is to describe the behavior of pre-cleavage ductile tearing and mode conversion to cleavage. The physical factors involved in this phenomenon have to be taken into account in the development of a fracture-mode-conversion model. Different fractographic features are important,

depending on the model used, i.e. void and inclusion volume fraction for void formation and coalescence models. Examinations of the fracture surfaces are being conducted to (1) characterize the extent of crack-tip blunting prior to crack growth; (2) identify and characterize the microstructural features associated with microvoid formation and growth; (3) identify and characterize the microstructural features responsible for the mode conversion to cleavage; and (4) describe the relationship between the ductile crack morphology and the trigger points at mode conversion. The determination of specific material parameters will include (1) the average void spacings of the major particles; (2) the initial void volume fraction; and (3) the volume fraction of nucleating particles. R-curve (J vs Δa) testing will be carried out for the SNUPPS material to be used for calibration of the fracture-mode-conversion model. Data from these tests will be used for calibration of the fracture-mode-conversion model. Results from these investigations will be used in the development of the fracture-mode-conversion model. The metallurgical investigations will be completed and the results presented in a letter report in FY 1995.

3.1.4.2 Development Of A Fracture-Mode-Conversion Model (Subtask 4.2) The development of a fracture-mode-conversion model was initiated in the FY 1994 performance period. The fracture-mode-conversion model will be used to predict ductile tearing preceding a cleavage crack initiation in the transition-toughness region. A finite-element code is being developed that analyzes very large 3-D solid models encountered in fracture mechanics studies of crack-tip fields and ductile crack growth. Static and dynamic solution capabilities are constructed on the framework of a linear-preconditioned solver implemented in an element-by-element format. A robust kinematic formulation including finite strains and large displacements is adopted. Nonlinear constitutive material models include rate-independent and rate-dependent Von Mises plasticity with various isotropic/kinematic hardening rules and a fully implicit implementation of the Gurson hole-growth model (with optional void nucleation and matrix visco-plasticity). An element death option facilitates removal of heavily damaged elements during crack-growth analyses. J-integrals along crack fronts are evaluated using a domain-integral methodology. The following items have been included in the model development: (a) geometry changes resulting from crack tearing extension; (b) effects of work hardening of the crack-tip material prior to crack resharpening; (c) void formation and coalescence models; (d) crack advance, based upon the Dodds J-R approach; and (e) development of an analytical technique that will permit an "adequately refined" crack-tip model to propagate though the material with the crack tip. Model development and evaluation will include consideration of the following factors: (1) mode conversion due to an increase in stress triaxiality with crack extension (leading to a higher degree of constraint and possibly following satisfaction of stress or stress-strain based criteria); and (2) breaking of any ductile ligaments behind the advancing crack-front leading to strain-rate sensitivity (i.e., rate-dependent plasticity); and (3) cleavage conversion criteria. Work in FY 1995 will also focus on the validation of the model with information obtained from the metallurgucal investigations (Subtask 4.1). The preliminary fracture-mode-conversion model will be completed and presented in a letter report in FY 1996.

As part of the model development, modifications to the Dodds-Anderson (D-A) toughness-scaling model will be carried out to render the model applicable to biaxial loading conditions. Recent fracture tests performed under biaxial bending loads at ORNL demonstrate an evolution of plastic deformation remarkably different from that observed in conventional, shallow-and-deep-notch fracture tests loaded in uniaxial bending. In the biaxial tests (1:1 ratio), plastic deformation remains strongly confined to the near tip region up to relatively large loads (and corresponding high crack-tip stresses) and then develops rapidly with only small additional load. This phenomenon has raised questions concerning the effects of crack-tip plastic strain on the D-A toughness-scaling model, which employs stressed volumes of material at the crack tip to correlate constraint affects on toughness across various specimens. Over the process zone in which cleavage fracture initiates ($r < \sim 2\text{-}5$ CTODs), sufficient plastic strain must be present to create cleavage nucleation sites that eventually trigger macroscopic fracture when applied (near-tip) stresses, considered in the D-A model, reach critical levels.

The original development of the D-A model assumed the presence of sufficient plastic strain over the cleavage process zone to provide nucleation sites. For conventional fracture specimens loaded in uniaxial bending and uniaxial tension, plastic-strain and crack-region stresses increase in roughly proportional fashion, generally with large plastic strains developing over the cleavage process zone early in the loading. This may explain the relatively good toughness correlations obtained for the D-A model for these conventional specimens.

In this work, a plastic strain threshold will be included in the D-A model to address explicitly the phenomenon observed in the biaxial bending tests. Material will be included in the stressed volume only when both the principal stress and plastic strain exceed specified values (plastic strain values estimated from available "plane-strain" tensile tests). The revised scaling model is expected to exhibit minimal differences for conventional fracture specimens, but for the biaxially loaded specimens the scaling curves of J_0 vs. J-specimen will differ significantly.

The generalized D-A constraint model will be completed and presented in a letter report at the end of the FY 1996.

3.1.4.3 Development Of A Predictive Engineering Methodology (Subtask 4.3) During the second half of FY 1995, the development of a predictive engineering methodology will be initiated using the results from the mode-conversion model. The model is intended for application in both deterministic and probabilistic fracture mechanics evaluations of RPVs. The status and progress made on this methodology development will be presented in a letter report in FY 1996 (same as letter report in milestone 4.2.C).

3.1.5 Fracture-Analysis-Methods Development And Applications (Task 5)

This task emphasizes the development and validation of computational methods for use in predictive fracture mechanics computer programs used for structural integrity assessments of nuclear reactor pressure vessels (RPVs). The validated fracture methodologies will be presented and published in appropriate forums as well as implemented into the FAVOR (Fracture Analysis of Vessels: Oak Ridge) computer code. FAVOR performs deterministic and probabilistic fracture analyses of aging embrittled clad RPVs subjected to transient conditions, such as pressurized thermal shock, in compliance with the applicable regulatory criteria.

The motivation for developing FAVOR was to consolidate the best attributes of OCA-P and VISA-II into a single validated, quality assured, user-friendly, and well documented RPV fracture mechanics code that complies with the applicable regulatory criteria. The ideas used in the development of FAVOR were derived from lessons learned during the integrated Pressurized Thermal Shock (IPTS) program, the Yankee Rowe review, and the Yankee Rowe sensitivity analysis. It is anticipated FAVOR will continue to evolve such that it continuously reflects the state-of-the art in pressure vessel fracture technology. Fracture technologies developed in this and other tasks will be implemented into FAVOR such that it contains all the elements of a comprehenesive methodology to perform generic and plant-specific fracture margin evaluations for RPVs.

FAVOR is applied within the HSST program to perform impact assessment analyses to determine the potential significance that research results would have in a regulatory analysis. FAVOR is applied to perform vessel integrity assessments in support of NRC evaluations of nuclear RPV integrity issues. FAVOR has been, and will continue to be, used extensively in the reevaluation of the PTS screening criteria and Regulatory Guide 1.154.

The personnel involved in this task have extensive experience in scientific software development and the application of computational fracture mechanics to the evaluation of pressure vessel fracture prevention margins.

3.1.5.1 Continuing Development of FAVOR A continuing objective in this subtask is the development of a comprehensive database of accurate validated stress intensity influence coefficients (SIFICs) for a range of inner-surface flaw geometries for the range of clad-RPV geometries that envelope the commercial pressurized water reactor (PWR) and boiling water reactor (BWR) vessel geometries in the united states. The long-term objective of this SIFIC database is to have the capability to generate SIFICs, and subsequently K_Is, for vessel geometries with an internal radius to wall thickness ratio of $(R_1 / t) = 10$ and 20. The incorporation of this SIFIC database into predictive fracture mechanics codes, such as FAVOR, will facilitate the generation of accurate fracture mechanics solutions for the range of flaw geometries required in structural integrity assessments of domestic U.S. PWR or BWR geometries.

During previous reporting periods, databases of SIFICS were generated for axially and circumferentially oriented inner-surface flaws with aspect ratios of 2, 6, 10, and infinity, applicable to clad rpvs with $(R_i / t) = 10$. This geometry is prototypical of a large percentage of the commercial PWRs in the United States. ABAQUS, a nuclear quality assurance certified (NQA-1) multidimensional finite element code with fracture mechanics capabilities, was used to generate the SIFICs. Where possible, these databases of SIFICs have been compared with those published by other investigators. These SIFICs have been published, presented in public forums, and implemented into FAVOR. FAVOR has been validated to produce Ki solutions that are within 1-2% of those obtained by direct ABAQUS three-dimensional finite element solutions.

During FY 95, SIFICs will be generated for axially and circumferentially oriented finite-length semielliptical inner-surface flaw geometries for clad RPV geometries with an (R_i / t) ratio of 20. SIFICs will be generated for both axially and circumferentially oriented inner-surface flaws with aspect ratios of 2, 6, 10, applicable to clad RPVS with an internal radius to wall thickness (R_i / t) ratio of 20. This geometry is prototypical of a large percentage of the commercial boiling water reactors (bwrs) in the United States. The matrix of fractional wall thicknesses for which SIFICs will be generated will be similar to that for RPVs with an internal radius to wall thickness (R_i / t) ratio of 10.

The following papers will be presented / published during FY 95:

Validation FAVOR Code Llinear Elastic Fracture Solutions for Finite Length Flaw Geometries - this paper will be presented / published at the 1995 asme pressure vessel and piping conference.

An Overview of FAVOr: A Fracture Analysis Code For Nuclear Reactor Pressure Vessels - this paper will be presented / published at the 1995 SMiRT (structural mechanics in reactor technology) conference.

The 9501 version of the FAVOR code, which contains the ABAQUS SIFIC librarires for axially and circumferentially oriented flaws with aspect ratios of 2, 6, 10, and infinity will be released to commerical and research organizations active in RPV safety analyses.

3.1.5.2. Pressurized-Thermal Shock (PTS) Applications The NRC plans to revise Regulatory Guide 1.154 (format and content of plant-specific pressurized thermal shock safety analysis reports). The objective is to publish a revised regulatory guide 1.154 that reflects the fracture technology developed in the last decade and lessons learned from the analysis of the Yankee Rowe nuclear plant. Technical bases must be developed to support this revision. Specific aspects of the PTS problem that are being revisited include thermal-hydraulics, human factors, PRA, and fracture mechanics analyses. This effort involves interaction between personnel from INEL (thermal-hydraulics), Sandia [probabilistic risk assessment (PRA)], and Oak Ridge (fracture mechanics) National Laboratories.

Currently, the NRC plan is to revise regulatory guide 1.154 according to a "two analysis" methods approach: (1) a best-estimate frequency of failure with specified flaw variables such as flaw density, flaw depths, and flaw lengths (2) a more-detailed PRA that determines a "mean" frequency of vessel failure. The more detailed PRA includes the uncertainty associated with thermal hydraulics and flaw-related variables.

During the previous reporting period, the workscope was divided into two phases: phase I is the development of technical bases and methodologies. Phase II will be demonstration analyses, i.e., a coordinated effort between the various laboratories to integrate and apply the revised technical bases and methodologies to plant-specific test cases.

3.1.5.2.a Phase I: Development of Technical Bases and Methodologies for Revisions to Regulatory Guide 1.154 The objective of phase I is the development of technical bases and methodologies to support revisions to Regulatory Guide 1.154. During FY 95, an objective of this subtask will be to complete the development of a revised fracture mechanics model. During the previous reporting period, PFM sensitivity analyses were performed to determine the potential impact of various modifications to the fracture mechanics model currently specified in Regulatory Guide 1.154. All flaws were located on the inner surface of the vessel, i.e., inner-surface breaking flaws. Specific fracture mechanics model assumptions examined included flaw geometry, the effect of clad, flaw density, and fracture initiation and arrest toughness. FAVOR was used to perform all fracture analyses. The results of these analyses and the HSST recommendations for fracture mechanics modifications will be documented in NRC Letter Report ORNL/NRC/LTR-94/31 entitled *Potential Modifications to the Fracture Mechanics Model in Regulatory Guide 1.154.*

Beginning in 1994, there was a NRC-directed interaction with INEL, Sandia, and PNL to develop a methodology for performing the NRC-specified "method 2" PTS analysis. The methodology includes the uncertainties associated with thermal hydraulics, transient initiating frequencies, and flaw-related parameters, as well as the degree of vessel embrittlement. The implementation of this methodology will require the development of a specialized version of FAVOR. During FY 95, work will be initiated on the development of this computer code.

3.1.5.2.c Review of PTS Screening Criteria During FY 95, the development of the PTS screening criteria (RT_{PTS} of 270°F for plates, forgings, and axial welds, and 300°F for circumferential welds) that was developed in SECY 82-465 will be reviewed. The PTS screening criteria, as developed from both deterministic (Appendix O in SECY 82-465) and probabilistic Appendices G and H in SECY 82-465) considerations will be be reconstructed. This will serve as a baseline for examining the impact upon the screening criteria of various fracture model modifications. Some of the fracture model modifications to be considered are as follows:

- the use of regulatory guide 1.99, revision 2 to predict the radiation-induced shift in rtndt.
- increasing the definition of one standard deviation for copper from 0.024 percent to 0.07 percent.
- inclusion of clad plasticity and fracture toughness
- various flaw geometries, aspect ratios of 2, 6, 10, and infinity
- inclusion of fracture initiation toughness correlation that includes the effect of shallow flaws and biaxial loading
- inclusion of plate regions
- various flaw densities

3.1.5.3 Provide Technical Support For NRC (a) This subtask provides for technical support to the NRC staff during ACRS /CRGR reviews and public comment period. (b) This subtask provides continuing technical support to the NRC staff in computational benchmark and specialists / experts meetings.

3.1.6 Material Property Data and Test Methods (Task 6)

The general work to be performed under this task emphasizes developing unique test methods, determining mechanical and physical properties of the materials needed for RPV fracture analyses and margin evaluations. Additionally, this task provides a direct liaison with the HSSI project (Job Code L1098), to obtain data and input regarding irradiation effects on materials. However, it does not perform irradiation experiments nor testing of irradiated materials. Two Subtasks within this task deal with the development of J-R curves for a number of heats of A302 grade B steel, and the development of dynamic fracture toughness curves under prototypical dynamic loading conditions.

3.1.6.1 Ductile Fracture Toughness of Plate Materials (A302-B) (Subtask 6.1) The objective of this Subtask is to develop ductile fracture toughness data, in the form of J-integral tearing resistance curves (J-R curves), for A302 grade B plate materials typical of those used in fabricating reactor pressure vessels. A previous experimental study with one particular heat of the A302 grade B plate material showed decreasing J-R curves with increasing specimen thickness. In FY 1994 several heats of A302 grade B steel were performed at multiple temperatures and in multiple orientations to obtain J-R curves. Compact specimens of 0.5T, 1T, 2T, and 4T size were tested to investigate the effect of specimen size on the J-R curves. Additionally, Charpy V-notch impact, tensile, and drop-weight tests were performed to characterize the materials and to determine RT_{NDT}s. The J-R curve testing program matrix was completed during the FY-1994 work period, with the exception of a series of tests with two heats to examine variability; this aspect of the project may be pursued at a future time. Most of the test results were reported in a letter report during the FY-1994 work period. The remaining efforts required for completion of the Subtask involve detailed analyses of the tests, to include re-analysis of selected test records in accordance with recently adopted procedures in the standard test practice, and preparation of a detailed NUREG report. A formal NUREG-CR report giving a detailed presentation and discussion of the results, as well as a detailed metallographic description of the materials, will be completed by August 31, 1995.

3.1.6.2 Dynamic Fracture Toughness Testing (Subtask 6.2) This Subtask is concerned with performing testing to determine the dynamic initiation fracture toughness of RPV materials at very high strain rates. An experimental program was started in the FY 1994 work period to obtain a systematic set of test data for dynamic fracture initiation toughness values at high strain rates applicable to PTS transients in RPVs. In PTS crack propagation analyses it is necessary to utilize dynamic fracture initiation and subsequent dynamic reinitiation fracture toughness values appropriate for crack-growth initiation, crack-arrest, and post-arrest crack-growth reinitiation conditions prior to final failure. The key issues are as follows:

- Due to a gradient in fracture toughness through RPV wall-thickness as a function of the temperature and irradiation embrittlement, a detailed dynamic analysis of crack propagation predicts a number of initiation and arrest events prior to a stable arrest. This analysis of dynamic crack initiation, propagation, arrest, and subsequent reinitiation during a postulated transients, such as a PTS event, requires the material's dynamic crack initiation, growth, crack-arrest, and reinitiation toughness values. Crack propagation and arrest are dynamic events and require dynamic fracture analysis methods for a more realistic prediction. Appendix A to Section XI of ASME code and Regulatory Guide 1.154 treat crack-arrest as a static event and incorporates dynamic considerations in the crack-arrest fracture toughness, K_{Ia} of ferritic steels. There has been little incentive, therefore, for the generation of data for dynamic fracture initiation, K_{Id}. Dynamic fracture toughness data are, therefore, very scarce.

- Prediction of reinitiation of an arrested cleavage crack is a key issue. Reinitiation could occur within a short time after the initial crack-arrest, due to dynamic response of the RPV in the presence of an extended crack, or it may occur later during a transient due to system re-pressurization, such as during a PTS transient Prediction of reinitiation is quite difficult [Ref. 1] due to sensitivity of the dynamic fracture toughness to the loading rates which can be very high after the initial crack-arrest.

- In the lower-shelf and in the brittle-to-ducule transition regions the fracture toughness of RPV ferritic steels decreases with increasing loading rates. The NRC funded test data [Ref. 2] show that the dynamic fracture initiation toughness, K_{Id}, of A533B steel decreases substantially with increasing loading rates.

- The dynamic analyses of HSST Wide Plate tests [Refs. 3-4] and the CE/EPRI crack-arrest specimens [Ref. 5] have shown that the reinitiations are predicted to occur at higher loading rates and at higher K_{Id} values than those covered by the NRC test data set [Ref. 2]. Therefore the test data in Ref. 2 are not adequate for performing dynamic response analyses of large-scale test specimens and RPVs. Hence, there is therefore, a need for generating additional test data at higher loading rates.

The objective of this Subtask is to generate dynamic plane-strain fracture initiation toughness test data, K_{Id}, to verify the accuracy at key selected points of, and extend further, the existing data set [Ref. 2] for A533 grade B class 1 steel, and to extend the data set to higher loading rates in the range of 10^5 to 10^6 ksi$\sqrt{in}$/second, and to find the effect of the normalized temperature $(T\text{-}RT_{NDT})$ on the K_{Id}. The toughness values for additional loading rates will be generated to extend the upper limit of the data set, as presented in the test specifications (Ref. 6).

Details of the work to be performed are defined in items 6.2.1 and 6.2.2 below. This development and material's data generation program is intended to include a broad range of test conditions, so that the dynamic fracture initiation toughness values determined, in addition to the values presented in Ref. [2], can address RPVs under most of the possible sets of transient loading conditions for which dynamic fracture toughness, K_{Id}, evaluation is appropriate.

Item 6.2.1: Dynamic Fracture Initiation Toughness Test Data Generation

The objective of this part is to select appropriately high-rates of loading (dKId/dt) and conduct dynamic fracture initiation tests at selected isothermal temperature conditions. The loading rates and the isothermal temperatures values will be selected to adequately cover a majority of anticipated transients for dynamic fracture evaluation of RPVs. Multiple specimens may be tested at the given test conditions to account for statistical variations in the material toughness data.

The verification of the data set [Ref. 2] at key values of the dependent variables, loading rates and temperature values, will also be performed to determine their accuracy. The data set [Ref. 2] will be updated and expanded with toughness values in Ref. 6. During the FY 1995 work period, acquisition of the test data on dynamic fracture initiation toughness under this Subtask will be completed.

Item 6.2.2: Test Data Interpretation and Toughness Determination

The item of the Subtask includes test data gathering, reduction and interpretation, determination of individual dynamic fracture initiation toughness values, and statistical analysis to obtain K_{Id} values at each loading rate and at the isothermal temperature conditions specified in Ref. 6. During the FY 1995 work period a test data report will be completed by the subcontractor.

<u>Technical References for Subtask 6.2:</u>

[1] J. Keeney-Walker and B. R. Bass, "A Comparison of Analysis Methodologies for Predicting Cleavage Crack Arrest of a Deep Crack in a Reactor Pressure Vessel Subjected to Pressurized Thermal-Shock Loading Conditions," USNRC Report NUREG/CR-5793, Oak Ridge National Laboratory, ORNL/TM-11969, September 1992.

[2] W. O. Shabbits, "Dynamic Fracture Toughness Properties of Heavy Section A533 Grade B Class 1 Steel Plate," NRC funded - HSST Technical Report No. 13, Westinghouse R&D Center (Report No. WCAP-7623), December 1970.

[3] R. H. Bryan et al., "Pressurized-Thermal Shock Test of 6-inch Thick Pressure Vessels, PTSE-2: Investigation of Low Tearing Resistance and Warm Prestressing," USNRC Report NUREG/CR-4888, Oak Ridge National Laboratory, ORNL-6377, 1987.

[4] D. J. Naus et al., "Crack-Arrest Behavior in SEN Wide Plates of Quenched and Tempered A533 Grade B Steel Tested Under Nonisothermal Conditions," USNRC Report NUREG/CR-4930, Oak Ridge National Laboratory, ORNL/TM-6388, August 1987.

[5] D. J. Ayres and R. J. Fabi, "Reactor Vessel Integrity Analysis Based Upon Large Scale Test Results," IAEA Committee on the Safety of Nuclear Installations (CSNI), Specialists' Meeting on: Fracture Mechanics Verification by Large-Scale Testing, Oak Ridge, TN., October 26-29, 1992, p. 585-598, NUREG/CP-0131, 1993.

[6] B. R. Bass, "Specification for the Dynamic Fracture Initiation Toughness Testing of a Reactor Pressure Vessel Steel," Specific. Report No. HSST-H06-94-001, Rev. 1, March 14, 1994, ORNL.

3.1.7 Integration Of Results Into A State-Of-The-Art Analysis Methodology (Task 7)

The objective of this task is to evaluate, interpret and apply the results of HSST program research to the regulatory process through interpretive reports, consulting to the NRC, and direct participation in the consensus codes and standards process. Accomplishing the objectives of this task requires that the experimental and analytical results produced by the other five research tasks be carefully evaluated, supplemented where necessary, and interpreted, along with other available results. In this process, the significance of research results must be clearly stated, taking full account of existing regulatory criteria, the principles of fracture mechanics, the theory of plasticity, and the fundamentals of structural strength and performance. The elements of this task are to (1) assess current regulatory fracture analysis methods, (2) recommend changes in the methodology to incorporate results from the HSST program research including (a) the evaluation of margins in the code fracture toughness curves and (b) the analytical and test investigation of crack-tip constraint effects associated with shallow flaws and biaxial loading, (3) implement technology transfer through participation in national and international codes and standards activities, and (4) provide technical assistance to NRC, as required, in document reviews and technical meetings. During the FY 1995 work period, significant activities in characterizing out-of-plane crack-tip constraint effects in the transition temperature region, cladding effects, and ductile-to-cleavage mode conversion effects will be performed in other tasks.

Pending the technical results from these efforts, this task will consist of the following Subtasks.

3.1.7.1 Assessment of Analysis Methods in Current Regulatory Applications (Subtask 7.1) This Subtask is directed towards a continuation of the assessment (started during FY 1994) of the fracture analysis methods used in current regulatory applications, building on the work done by the ASME Section XI Subgroup on Evaluation Standards, and published in EPRI report number TR-100251 (January 1993). An assessment of the state of Technology in ASME, Section XI Appendix G will be continued, aiming at the publication of an interpretive NUREG/CR report in FY 1996, which will address at least the following technical issues:

(i) Stress-intensity factor, K_P (due to pressure) and K_T (due to temperature gradient), solutions for axially and circumferentially oriented flaws in a range of sizes that are as shallow as 0.05t (t = wall thickness), and as deep as 0.35t (to include Appendix K and code case N-512 solutions). The flaw aspect ratio, 2c/a, and the vessel R_i/t ratio also will be variables, to envelope the PWRs and BWRs in the U.S.

(ii) Cladding effects for the range of variables considered above; additionally, the work will address cladding thickness, the stress relief and stress-free temperatures, cladding mechanical properties (taken from the HSST program for thermal aging and irradiation effects data), and the analytical expressions for computing K_{CLAD}.

(iii) The need to include residual stresses in the regulatory analysis; this evaluation will also include a discussion on methods needed to estimate them.

(iv) The uncertainty in the overall determination of $K_{APPLIED}$ and its potential impact on the analysis margin; the work will make an assessment of biaxial loading effects, and their influence on overall accuracy. The work will also assess material property uncertainties, and how these could impact the margin needed to assure a "conservative" analysis.

3.1.7.2 Incorporate Crack-tip Constraint Effects (Subtask 7.2) Planar shallow-flaw specimens have been shown to exhibit a significant toughness increase over deep-flaw specimens due to in-plane constraint effects. The objective of this Subtask is to recommend changes in the current procedures for analyzing shallow surface flaws in RPVs. These recommendations will include the in-plane shallow-crack increase in toughness and the available results on influence of biaxial loading, since all shallow surface flaws in a RPV are subject to biaxial loading. Interpretation of past (HSST generated) and present (the shallow-crack beams tested at NSWC and the full-thickness clad beams tested at NIST) data will be continued. Strain gradient influences will be considered. In addition, this Subtask will evaluate the need for, and if necessary recommend, methods to be used by the ASME code for determining fracture margins for shallow-surface flaws subjected to biaxial nominal stresses. The effects of biaxial loading on the opening-mode stress intensity factor (K) under elastic-plastic loadings prototypic to RPV belt-line region will be considered.

3.1.7.3 Participation in National and International Codes and Standards Organizations (Subtask 7.3) The objective of this Subtask is to reduce the results of the HSST program to practice through participation in various national and international codes and standards organizations. Based on current initiatives in national codes and standards organizations, the following activities will be included in the HSST program during the FY 1995 work period:

(i) ASME Section XI, Working Group on Flaw Evaluation

(ii) ASME Section XI, Working Group on Operating Plant Criteria

(iii) ASME Section XI, Subgroup on Evaluation Standards

(iv) ASME Section XI, Task Group on Application of NDE to Plant Operating Criteria

(v) ASTM Committee E-08 on Fatigue and Fracture, with emphasis on Subcommittees E08.08 (elastic-plastic fracture mechanics technology), E08.04 (structure applications), and E08.07 (linear-elastic fracture).

(vi) The Welding Research Council, Pressure Vessel Research Materials and Fabrication Division (in particular: committees on failure modes of components, and on welds, attended by Professor S. T. Rolfe, who will furnish reports to the HSST program.

Participation in these organizations during the FY 1995 work period will include attending the meetings of each group, performing analyses to evaluate proposals put before the groups, and preparing and making presentations before the groups.

Meeting reports describing participation in these groups will be submitted within 30 calendar days of each meeting. The reports will summarize significant issues considered during the meeting, the results of any votes taken and the participant's vote on those issues, and any future issues that are believed to relate to the HSST program or other related NRC funded projects.

3.1.7.4 Special Technical Assistance (Subtask 7.4) The objective of this Subtask is to provide short-term technical assistance to the NRC in reviewing technical documents, and participating in various technical meetings with and on behalf of the NRC. The specific activities to be performed during this work period are described below. However, it should be noted that other activities may be added during the FY 1995 work period by modification of the statement of work.

(i) A prompt transfer of HSST program output to national consensus standards (ASME, ASTM and PVRC/WRC) is to be carried out under this Subtask. Upon approval by the NRC project manager, specific technical issues will be addressed as they arise. During the FY 1995 work period, this will include:

(1) Presentations to ASME Section XI of a tabulation of stress-intensity-factor influence coefficients for finite-length surface cracks (including and the cladding effects) and the basis for selection of safety factors for nuclear structural systems, and

(2) Presentations to PVRC/WRC committees, of HSST program results on the effect of shallow flaws on fracture toughness under prototypic conditions in reactor vessels.

(ii) Continue leading the development and balloting of an ASTM standard for the measurement of fracture toughness in the brittle-to-ductile transition temperature region with small specimens. Insure that the technical basis for the standard is documented.

(iii) Provide assistance to NRC in resolving public comments and issues related to the draft regulatory guide on low Charpy upper-shelf energy materials. This will include continuing the investigation on the technical basis for the equations for stress intensity factor (k) under steady-state and transient thermal cooldown and pressure loadings.

3.2 FY 1996

3.2.1 Program Management (Task 1)

The program direction, monitoring and control, subcontract management, quality control, and communications activities defined in section 3.1.1, will be continued in FY 1996. Twelve monthly progress reports and two semiannual reports will be produced. Progress towards meeting the program objectives will be assessed by maintaining a continuing surveillance of output from the program research activities. Results from the surveillance activities will be used to periodically assess the effectiveness of the program plan, and identify any areas where adjustments to the program plan would be beneficial. No adjustments to the approved program plan will be made without the prior written approval of the NRC HSST Project Manager.

Material from the reactor pressure vessel from Pressure Vessel Research Users' Facility (PVRUF) will be procured and placed in the HSST program materials storage yard at the Y-12 site at Oak Ridge National Laboratory. The material to be procured will include (a) material suitable for the fabrication of future large-scale test specimens, and (b) material previously inspected by Pacific Northwest National Laboratory using the SAFT ultrasonic inspection system.

Contacts will be maintained with both domestic and foreign research organizations and professional societies involved in the development and application of technology for the structural integrity assessment of nuclear reactor pressure vessels. Areas where direct interaction with these organizations would be beneficial will be identified. Arrangements for an interchange of fracture-technology research results with selected organizations will be made when approved by NRC.

Papers will be prepared presenting an overview of the HSST program research results and providing an assessment of the impact of those results on the structural integrity assessment of nuclear reactor pressure vessels. These papers will be presented at the NRC Water Reactor Safety Meeting, professional society meetings, and at special purpose meetings and workshops as designated by NRC.

3.2.2 Constraint-Effects Analytical Development and Validation (Task 2)

3.2.2.1 Biaxial-Loading-Effects Validation Testing (Subtask 2.1). The effort in this Subtask is completion of and a direct extension of the verification phase biaxial-loading-effects testing initiated during the FY 1995 performance period. All of the validation tests will have been performed on specimens with a single flaw depth (one a/W ratio) and of a single specimen size. It is thus required that investigations be performed (a) to quantify the applicability of the constraint methodologies for different shallow-flaw depths and (b) determine the transferability of the methodology to predicting behavior in thicker sections (approaching those of an RPV thickness). Tests for (b) will be restricted to constant-depth 2-D flaws.

3.2.2.1.1 Verification-Phase Testing (Subtask 2.1.1) The verification matrix tests will be completed during this performance period. Two letter reports will be prepared, one on the Phase I verification testing and a summary report for this completed verification matrix.

Cruciform testing will be initiated to study the combined influence of flaw depth and biaxiality on fracture toughness. The intermediate size specimen, the same size as that used for the verification tests and test material will be used. Two additional flaw depths, tentatively selected as a/W = 0.05 and a/W = 0.15, will be used. Two biaxial load ratios are specified. The proposed test matrix is shown in Table 2.2. A total of 8 tests are included for preliminary verification of the effects of flaw depth and biaxiality on fracture toughness. The baseline and the most severe biaxiality conditions, as determined by Phase I of the verification testing, will be used. All specimens will be fabricated during this performance period and testing will be completed in early FY 1997. The source material for these tests will also be the heat treated HSST Plate 14. Fractographic information will be generated for a select number of fracture surfaces. Location of initiation sites, the amount of ductile tearing, and the extent of the plastic zone size developed around the flaw tip will be determined. Full definition of the test matrix, including the appropriate combination of test parameters, will be preceded by finite element analyses using a refined mesh tip model. These analyses will be used to define the limits in flaw depth where biaxial loading would be expected to have an effect on fracture toughness. Small-scale specimens, i.e., plane-strain, CTOD, slow-bend Charpy, will continue to be utilized, as appropriate, to assist in interpretation of the test results and in validation of the strain-based constraint model. A letter report will be prepared within 30 days after test completion and will provide test results and interpretation.

The second series of cruciform tests will be performed to verify transferability of the constraint methodologies to thicker sections. Verification of transferability of the technology is necessary for application of these methodologies to RPVs. A large-scale specimen will be designed and used for these tests. This specimen will be a simple scale-up of the intermediate-scale specimen and will not require testing development for implementation. The specimens will be machined from plate material with the longitudinal beam being a homogeneous unit. All specimen details, flaw geometry, load-diffusion-control slots, etc., will be integrally machined requiring only one EB weld setup to attach the transverse beam arms after the crack in the specimen has been fatigue presharpened.

Table 2.2 Proposed Test Matrix for Flaw Depth Effects Verification Testing (Subtask 2.1.1)

Batch #	Normalized Test Temperature	a/W Ratio	Load Biaxiality Ratio	Notes
1	TBD	0.05	LR1	a,b
2	TBD	0.05	LR1	a,b
3	TBD	0.15	LR2	b,c
4	TBD	0.15	LR2	b,c

Test Specific Notes:

a. The a/W ratio is preliminary awaiting detailed. pretest analyses
b. LR1 is defined as the baseline biaxial load ratio
c. LR2 is defined as the most severe biaxial load ratio

General Notes:

d. All tests will be conducted with the cruciform specimen developed during FY 1993-95 using a 2-D flaw configuration with the specified a/W ratio.
e. All specimens will be tested in the heat-treated condition to assure prototypic stress-strain response.
f. A batch refers to two specimens tested at identical conditions. A total of eight specimens or four batches are being specified for this matrix.
g. Test temperature is specified to be the same as that for the verification matrix.
h. Load ratio is denoted as transverse load/longitudinal load.

It is proposed that two flaw depths and two biaxial load ratios be examined in the large-scale specimen tests. The flaw depths will be determined based on analyses as were performed above while the load ratios will be the same as those for the flaw depth matrix. Fabrication and testing of these specimens will be initiated during the FY 1996 performance period. It is planned that two specimens of this type will be completely fabricated during this performance period. All testing will be completed during the FY 1997 performance period. Any additional characterization of heat treated Plate 14 material will be performed in this Subtask.

Table 2.3 Proposed Test Matrix for Large-Scale Specimen Biaxial Effects Verification Testing (Subtask 2.1.1)

Specimen #	Normalized Test Temperature	a/W Ratio	Load Biaxiality Ratio	Notes
1	TBD	0.05	LR1	a,b
2	TBD	0.05	LR1	a,b
3	TBD	0.15	LR2	b,c
4	TBD	0.15	LR2	b,c

Test Specific Notes:

a. The a/W ratio is preliminary awaiting detailed, pretest analyses
b. LR1 is defined as the baseline biaxial load ratio
c. LR2 is defined as the most severe biaxial load ratio

General Notes:

d. All tests will be conducted with the scaled up, large-size cruciform specimen using a 2-D flaw configuration with the specified a/W ratio.
e. All specimens will be tested in the heat-treated condition to assure prototypic stress-strain response.
f. Test temperature is specified ito be the same as that for the verification matrix.
g. Load ratio is denoted as transverse:longitudinal load.

3.2.2.1.2 Analysis Support of Test Data (Subtask 2.1.2) Analyses will be required to establish the a/W ratios to be used for both test matrices initiated during this performance period. Detailed finite-element analyses will be performed using a design-type FEA model which is of sufficient refinement to establish test conditions. As was done previously, analysis of the tests will be performed to determine the toughness from the experimental data. Estimates of the P vs. CMOD η-factors required to interpret the test data as a function of crack depth, temperature, and load ratio, will be developed. The material properties used in the analytical model will be representative of the test material near the flaw tip. Both pre- and post-test analysis will be performed to provide test guidance. Required modeling refinements or modifications will be performed using post-test evaluations of deformation behavior. Fracture toughness estimates will be developed for all tests. Refined crack-tip modeling will be conducted as a part of Subtask 2.2. to provide comparisons between computed and measured mechanical response.

A letter report detailing the test and analysis results for the flaw depth matrix specimens will be issued by the end of the performance period. The report will include test results, analysis results, test and analysis comparisons, η–factors used to determine toughness from the test data, summary fractographic results, and preliminary interpretation of the toughness results. Quantification of the effect of flaw depth and biaxial loading on fracture toughness and an assessment on the scatter of toughness results will be included.

A limited number of small-scale fracture specimens will be tested to support constraint model development and to assist interpretation of analysis results. Plane-strain tensile specimens will be tested to measure the fracture ductility under plane-strain constraint conditions. The specimens will be machined from the same material as that used for the development phase specimens. A new specimen type will also be machined and verification tests performed. Using this specimen, measurements of CTOD at fracture can be made directly, and the relationship between initial crack-tip radius, CTOD at failure, and failure energy can be investigated. Results from these tests will be used, together with the results from the development phase cruciform tests, to further evaluate the newly proposed stress-strain-based constraint methodology. Tests of this type will also be performed on material from the heat treated Plate 14. Data from these tests, in conjunction with the stress-strain-based constraint model, will be used to generate pretest predictions of fracture behavior for the verification phase cruciform specimens.

The deliverables for Subtask 2.1 in FY 1996 are letter reports on Phase I verification testing, and a summary letter report on the verification-phase testing.

3.2.2.2 Constraint Effects Correlation Development and Verification (Subtask 2.2). **Assessment and refinement of existing and/or modified stress-based- and stress-strain-based dual-parameter fracture methodologies will be continued. Evaluation of the candidate fracture methodologies will require performance of detailed, near-crack-tip finite-element fracture mechanics analyses of (a) the cruciform specimens tested under the loading effects validation and the flaw-depth phases of Subtask 2.1 above, (b) the full-thickness clad beam specimens tested at NIST under Subtask 3.3, and (c) the clad cruciform beams being tested under Subtask 3.4. If identified, alternative constraint methodologies will be investigated for feasibility of their potential development and validation. The analytical investigations will be supplemented by metallurgical examinations of selected fracture surfaces from shallow-flaw fracture toughness specimens tested. The fractographic information will be used in the continuing assessment, validation, and development of a strain-based dual-parameter fracture toughness correlation.**

The deliverable for Subtask 2.2 is a letter report summarizing progress made during this performance period.

3.2.3 Evaluation of Cladding Effects (Task 3)

3.2.3.1 Quasi-Static Clad-Yielding-Model Development (Subtask 3.1) Influence-coefficient methodology based on LEFM concepts is used in the FAVOR PFM code to perform deterministic and probabilistic RPV structural integrity assessments. As a near-term refinement in the assessment methodology, the development of a generic clad yielding model will be completed and implemented in the FAVOR program during the FY 1996 work period. The generic model will incorporate clad yielding into the calculations, while permitting the LEFM influence coefficient approach to be retained in the presence of the cladding nonlinear response.

During the FY 1996 work period, the performance of the generic clad yielding model will be evaluated through applications to RPV integrity assessments. Geometries, material and toughness properties, as well as transient loading conditions will be defined in an analysis matrix. Assessments of the conditions defined in the analysis matrix will be performed using the FAVOR code. Further refinements of the generic model will be formulated and implemented in FAVOR based on the results of these assessments. These refinements may require additional deterministic 3-D elastic-plastic finite element analyses of shallow surface cracks in RPV models. A letter report describing the results of the integrity assessments and refinements of the generic clad yield stress model will be issued by the end of the work period.

Specific accomplishments planned for this Subtask in the FY 1996 performance period are as follows:

- complete formulation of analysis matrix for RPV integrity assessments using the generic clad yielding model installed in FAVOR.
- complete applications of the generic clad yielding model to RPV structural integrity assessments based on the analysis matrix.
- formulate and implement refinements of the generic clad yielding model based on interpretations of results from RPV structural integrity assessments.
- issue a letter report on interpretations of RPV structural integrity assessments and further refinements of the generic clad yielding model.

3.2.3.4 Biaxial Clad Cruciform Specimen Testing and Analysis (Subtask 3.4) During the FY 1996 performance period, testing will be completed for six development clad cruciform specimens and for the balance of the test matrix defined in Table 3.1, i.e., groups 1-3 in Phase I and groups 4-9 in Phase II. Thus, a total of twenty-four specimens will be tested in this period.

Test results from the Phase I set will provide guidance for further investigation of variables associated with cladding effects on crack initiation and propagation. These variables include crack geometry (depth and length), cladding thickness, cladding residual stresses, cladding deposition direction, HAZ, as well as material and fracture toughness properties associated with the various regions.

Phase II of verification testing will examine the propensity for crack initiation over the mid-transition temperature region as a function of crack geometry. Parameters defining crack geometries for tests 6–9 will be specified after sufficient data become available from the first test series. The effects of some of the other variables identified above will be investigated in additional series of tests to be performed under Task 2 utilizing the cruciform geometry.

Pretest and post-test computational analyses of the clad cruciform specimens will be made and interpretation of the test results will be made. Also, finite-element analyses of the near-crack-tip region of the test specimens will be performed. A letter report will be issued by the end of performance period describing progress in the testing and analysis of clad cruciform specimens. The results obtained from testing and analysis in this Subtask will be provided to Subtask 2.2 for developing-constraint effects correlations and verification.

Specific accomplishments planned for this Subtask in the FY 1996 performance period are as follows:

- complete development testing of six clad cruciform specimens,
- complete fabrication of groups 1-3 clad cruciform specimens for Phase I verification testing,
- complete groups 1-3 specimen tests for Phase I verification testing,
- complete selection of surface-crack geometries and test parameters for Phase II of verification testing,
- complete fabrication of groups 4-9 clad cruciform specimens for Phase II verification testing,
- complete groups 4-9 specimen tests for Phase II verification testing,
- complete posttest computational analyses of clad cruciform specimens, and
- issue letter report describing progress in testing and analysis of clad cruciform specimens.

<u>3.2.3.5 Large-Scale Clad Cruciform Specimen Testing and Analysis (Subtask 3.5)</u> During the FY 1995 performance period, initial preparations were begun for a large-scale clad cruciform testing program to investigate the influence of cladding, flaw depths, and biaxial-loading ratios on fracture toughness. The specimens will be sufficiently large to circumvent some difficulties associated with transfer of fracture toughness data from smaller laboratory-scale specimens to full-scale structures. The servo-hydraulic test machine employed by the HSST program at ORNL was modified to increase both the total load capacity of the test fixture and the size of the beam specimen that can be tested.

A preliminary test matrix is provided in Table 3.2. The clad cruciform specimens will be fabricated from SNUPPS shell material in the "as received" condition. The test section will contain a through-clad surface flaw located in clad-weld material. The selection of test parameters such as crack geometry, test temperature, loading ratios, etc., will be strongly influenced by results generated from the series of medium-thickness clad cruciform specimens described in Subtask 3.4.

During the FY 1996 performance period, a fitness demonstration will be completed for the test facility and test procedures using a dummy large-scale cruciform specimen fabricated for that purpose. Also, any necessary modifications of hardware or procedures identified in the first large-scale test will be completed. A letter report will be issued by the end of performance period describing progress in the large-scale clad cruciform testing program.

Specific accomplishments planned for this Subtask in the FY 1996 performance period are as follows:

- complete fabrication of a dummy large-scale cruciform specimen for a fitness demonstration of test facility,
- complete assembly and installation of the test fixture for large-scale clad cruciform specimen testing,
- complete a fitness demonstration of the test fixture and procedures using the dummy specimen, and
- issue a letter report on progress made in testing program during performance period.

<u>3.2.4 Ductile-to-Cleavage Fracture Mode Conversion (Task 4)</u>

<u>3.2.4.3 Development of a Predictive Engineering Methodology (Subtask 4.3)</u> A methodology will be developed to include the preliminary fracture-mode-conversion model in deterministic and probabilistic fracture mechanics analyses. The fracture-mode-conversion model must contain a viable model of cleavage initiation for stationary cracks (i.e., no stable tearing) and a ductile tearing model which provides output data that represent essential input to the selected cleavage model for predicting cleavage initiation. Several dual-parameter methodologies have been investigated to quantify the effects of specimen geometry and loading conditions on crack-tip constraint. The existing dual-parameter methodologies include both stress-based and stress-strain based characterizations of cleavage fracture. The validated model for cleavage fracture must successfully predict the effects of both uniaxial and biaxial loading on shallow-flaw fracture toughness in the transition region of RPV steels. Functional requirements for the ductile tearing models include the following: (a) reproduce J_R-curve test data; (b) require only input data that are validated and readily available; and (c) provide output that includes crack-tip radius and crack-plane plastic zone width as a function of crack growth. The methodologies for ductile tearing include

constitutive formulations that describe progressive damage and material softening of the local crack-tip region and parametric correlations of J_R-curve data with controlled changes in crack-tip constraint.

3.2.4.3.1 Methodology Development (Subtask 4.3 A) Performance assessments based on applications of the candidate cleavage and ductile tearing models to measured data from RPV steels will provide necessary input for defining the tearing-to-cleavage mode-conversion model. The preliminary fracture-mode-conversion model which includes both cleavage initiation and ductile tearing models will undergo validation procedures. A detailed parametric study will be performed in FY 1996 with the preliminary model for a relevant range of:

(a) geometries,
(b) transients, and
(c) loading conditions.

Modifications will be made to the fracture-mode-conversion model based on the validation study. As part of the model modifications, an investigation will be carried out to determine the difference in the stress field ahead of a growing crack using the Gurson model and crack-tip-opening angle failure criteria. Also, the affect of pre-cleavage ductile tearing on the D-A toughness scaling model and Weibull stress calculations will be investigated.

Initial empirical relationships will be generated from the final analysis results.

3.2.4.3.2 Reports (Subtask 4.3 C) The preliminary methodology to include the fracture-mode-conversion model in fracture mechanics analyses will be presented in a letter report in FY 1997.

3.2.4.3.3 Validation Testing (Subtask 4.3 D) The predictive engineering methodology will undergo validation procedures in FY 1997. A test matrix will be defined for the cruciform validation tests in FY 1996 that will include pre-cleavage ductile tearing. The test matrix will include: (1) specimen type, (2) crack geometry, and (3) test temperatures and loading conditions.

3.2.5 Fracture Analysis Methods Development and Applications (Task 5)

3.2.5.1 Continuing Development of FAVOR (Subtask 5.1) The stress intensity influence coefficients (SIFICs) that were generated during 1995 (SIFICs for axially and circumferentially oriented inner-surface flaws with aspect ratios of 2, 6, 10, applicable to clad RPVs with an internal radius to wall thickness (R_i / t) ratio of 20) will be implemented into the FAVOR computer code. The implementation of the SIFIC database into FAVOR will be validated by comparing ABAQUS direct 3-D finite element solutions with FAVOR solutions.

3.2.5.2 PTS Applications (Subtask 5.2) During FY 96, work will continue on the development of the specialized version of FAVOR module to perform "method 2" PTS analyses. The NRC has specified that the uncertainty associated with flaw-related data in welded regions be incorporated into the "method 2" type of analysis by using the PRODIGAL computer code. The PRODIGAL code is an expert-based system (developed by Rolls Royce, Inc. in the United Kingdom) that generates predictive probabilistic distributions of flaw densities, flaw locations in the RPV wall (surface breaking and/or embedded flaws), and flaw sizes introduced into welded regions during fabrication. This necessitates a software interface between the specialized version of FAVOR and PRODIGAL. During FY 96, work will be directed toward the development of this software interface.

3.2.5.2.c Review Of PTS Screening Criteria (Subtask 5.2.c) During FY 95, the development of the PTS screening criteria, as developed in SECY 82-465, from both deterministic and probabilistic considerations was reviewed and reconstructed. During FY 96, a letter report entitled "Review of the Pressurized-Thermal Screening Criteria for Embrittled Pressurized Water Reactor Pressure Vessels" will be issued.

3.2.5.3 Provide Technical Support for NRC (Subtask 5.3) (a) This subtask provides for techical support to the NRC staff during ACRS /CRGR reviews and public comment period. (b) This subtask provides continuing technical support to the NRC staff in computational benchmark and specialists / experts meetings.

3.2.6 Material Property Data and Test Methods (Task 6)

Subtask 6.1 will have been completed during FY 1995. For Subtask 6.2 on Dynamic Fracture Toughness Testing, an interpretative NUREG/CR report on dynamic fracture initiation toughness data in the ductile-to-brittle transition region will be completed by the end of December 1995. The report will provide a detailed presentation of the dynamic fracture toughness test results and a comparison with previously obtained data.

3.2.7 Integration Of Results Into A State-Of-The-Art Analysis Methodology (Task 7)

The objective of this task continues to be the evaluation, interpretation and application of the results of HSST Program research to the regulatory process through interpretive reports, consulting to the NRC, and direct participation in the consensus codes and standards process. The NRC has elected to base its regulation of the nuclear power industry, as much as possible, on industry consensus codes and standards, making direct participation in the development of these standards an activity of prime importance. An assessment of the fracture analysis methods used in current regulatory applications, begun in FY 1994 and continued in FY 1995, will be documented in a NUREG report. During FY 1996, significant research results will become available from Tasks 2, 3, and 4, including additional unclad cruciform and full-thickness clad beam fracture toughness data, biaxial and shallow-crack constraint analysis results, clad yielding analyses, and computational studies of fracture mode conversion from ductile tearing to cleavage. These results will be evaluated, organized, and used as part of the initial basis for a comprehensive fracture analysis methodology for reactor pressure vessels. During FY 1996, significant progress is also anticipated in the development and balloting of an ASTM standard for establishing fracture toughness values in the transition range based on small-specimen test data. The descriptions and titles of the Subtasks in Task 7 will remain the same as for FY 1995, except that the scope of Subtask 7.2 will broaden and its title will change from "Incorporate Crack-Tip Constraint Effects" to "Results Incorporation into a State-of-Art Analysis Methodology." A letter report concerning interim recommendations for considering shallow-flaw and biaxial-loading effects on fracture toughness will be issued early in FY 1996. Meeting reports documenting business conducted at consensus codes and standards meetings will be transmitted to the NRC Project Manager within a month after the meetings.

3.3. FY 1997

3.3.1. Program Management (Task 1) The program direction, monitoring and control, subcontract management, quality control, and communications activities defined in sections 3.1.1 and 3.2.1, will be continued in FY 1997.

3.3.2 Constraint Effects Analytical Development and Validation (Task 2)

3.3.2.1 Biaxial-Loading-Effects Validation Testing (Subtask 2.1) Constraint methodology testing will be completed in this performance period.

3.3.2.1.1 Verification-Phase Testing (Subtask 2.1.1) Large-scale cruciform testing to verify transferability of the constraint methodologies to thicker sections will be completed. Fabrication and testing of these specimens was initiated during the FY 1996 performance period. There will be two specimens of this type fabricated and three tested during this performance period. Small-scale specimens will continue to be utilized to assist in interpretation of the test results and in validation of the strain-based constraint model.

3.3.2.1.2 Analysis Support of Test Data (Subtask 2.1.2) Analyses of the tests will be performed to determine the toughness from the experimental data using the procedures developed in previous years. A letter report detailing the test and analysis results for the large-scale test matrix will be issued by the end of the performance period. The report will include test and analysis results, fracture toughness values, and all factors relevant to determination of toughness from the test data. An assessment of limitations, and/or applicability of use of the developed constraint methodologies for transferability will be included in the letter report.

The deliverable for Subtask 2.1 in FY 1997 is a letter report on the large-scale 2-D flaw biaxial test results.

3.3.2.2 Constraint Effects Correlation Development and Verification (Subtask 2.2). A NUREG/CR report will be prepared by the end of this performance period to summarize the effort to assess and refine existing and/or modified stress- and stress-strain-based dual-parameter fracture-toughness-constraint-effects methodologies. Work performed in prior years of this activity will be completed by application of the candidate fracture-toughness-constraint-effects methodologies to (a) the large-scale cruciform specimens tested under Subtask 2.1 above, and (b) the large-scale clad cruciform beams being tested under Subtask 3.4. The analytical investigations will be supplemented by metallurgical examinations of selected fracture surfaces from shallow-flaw fracture toughness specimens tested.

The deliverables for Subtask 2.2 in FY 1997 is a summary NUREG/CR report covering the assessment of the different constraint methodologies considered under this task.

3.3.3 Evaluation of Cladding Effects (Task 3)

3.3.3.1 Quasi-Static Clad-Yielding-Model Development (Subtask 3.1) Evaluation of the generic clad yielding model through applications to RPV integrity assessments will be initiated during the FY 1996 performance period. Refinements of the generic model will be formulated and implemented in FAVOR based on results from these assessments.

During the FY 1997 work period, evaluation and further refinements of the updated clad yielding model based on RPV integrity assessments will be completed. These assessments will incorporate relevant shallow-crack biaxial data provided by the intermediate-scale clad cruciform testing program conducted in Subtasks 2.1 and 3.4 during the FY 1996 performance period. A NUREG report will be completed during the performance period that discusses model development, validation procedures applied to the model, applications of the model to RPV assessments, and limitations of the formulation.

Specific accomplishments planned for this Subtask in the FY 1997 performance period are as follows:

- complete applications of an updated clad yielding model to RPV integrity assessments,
- formulate refinements of an updated model based on interpretations of results from RPV integrity assessments,
- complete implementation of refinements to the clad yielding model in the FAVOR code, and
- issue a NUREG report on model development, validation procedures, interpretations of RPV integrity assessments, and limitations of model.

3.3.3.4 Biaxial Clad Cruciform Specimen Testing and Analysis (Subtask 3.4) Testing and analyses of the intermediate-scale clad cruciform specimens described in Table 3.1 (Phases I and II) will be completed in the FY 1996 performance period. During the FY 1997 period, a comprehensive evaluation of the intermediate-scale clad cruciform testing program will be conducted to determine the impact of results from the testing program on fracture prediction methodologies and on RPV integrity assessments.

Specifically, assessments of stress-based and strain-based dual-parameter fracture toughness correlations will be carried out through applications of these methodologies to the shallow-flaw clad biaxial and uniaxial toughness data base. Also, PFM analyses will be performed with the FAVOR computer program to determine the influence of the fracture toughness data base on the conditional probability of crack initiation in representative RPVs subjected to severe PTS transients and to P-T loading transients. These PFM analyses will utilize fracture toughness curves derived from the shallow-flaw clad biaxial and uniaxial toughness data base. A NUREG report will be completed during this work period that provides a comprehensive evaluation of the clad-cruciform testing program and the implications of the shallow flaw toughness data base for RPV integrity assessments.

Specific accomplishments planned for this Subtask in the FY 1997 performance period are as follows:

- complete assessment of dual-parameter fracture toughness correlations applied to interpretation of shallow-flaw clad biaxial and uniaxial toughness data base,
- complete evaluation of the influence of shallow-flaw clad biaxial and uniaxial toughness data base on RPV integrity assessments, and

- issue NUREG report providing a comprehensive evaluation of results from the intermediate-scale clad cruciform testing and analysis program.

3.3.3.5 Large-Scale Clad Cruciform Specimen Testing and Analysis (Subtask 3.5) During the FY 1997 performance period, fabrication and testing will be completed for the large-scale cruciform specimens given in Table 3.2. The clad cruciform specimens will be fabricated from SNUPPS shell material in the "as received" condition. The test section will contain a through-clad surface flaw located in clad-weld material. The selection of test parameters such as crack geometry, test temperature, loading ratios, etc., will be strongly influenced by results generated from the series of medium-thickness clad cruciform specimens described in Subtask 3.4.

Following completion of each test, post-test finite-element near-crack-tip analyses of the specimen and correlations will be performed with the selected constraint-effects model (from Subtask 2.2). Experimental data from any specimens exhibiting pre-cleavage stable tearing will provide input for the assessment of fracture-mode-conversion models developed under Task 4 for the ductile-to-brittle transition temperature region. A comprehensive NUREG report will be issued by the end of performance period which describes results and conclusions derived from the large-scale clad cruciform testing program. Results from the large-scale testing program will also provide input to the comprehensive evaluation in Subtask 3.4 of the influence of the shallow-flaw clad biaxial and uniaxial toughness data base on RPV integrity assessments.

Specific accomplishments planned for this Subtask in the FY 1997 performance period are as follows:

- complete fabrication of first large-scale clad cruciform specimen for verification testing,
- complete readiness review for first large-scale clad cruciform test,
- complete verification testing of first large-scale clad cruciform specimen,
- complete any necessary modifications of procedures or hardware for conducting tests of large-scale clad cruciform specimens,
- complete computational analyses of first large-scale clad cruciform specimen,
- complete computational analyses of large-scale clad cruciform specimens for verification testing,
- complete fabrication of remaining large-scale clad cruciform specimens,
- complete verification testing of remaining large-scale clad cruciform specimens,
- complete computational analyses of remaining large-scale clad cruciform tests,
- complete interpretations of large-scale data for applications to fracture models evaluated in Tasks 2 and 4, and
- issue NUREG report on comprehensive interpretation and evaluation of large-scale clad cruciform testing program.

3.3.4 Ductile-to-Cleavage Fracture Mode Conversion (Task 4)

3.3.4.3 Development of a Predictive Engineering Methodology (Subtask 4.3) Emperical relationships will be implemented in deterministic and probabilistic codes, such as FAVOR (Subtask 4.3.A). The preliminary methodology for including the completed fracture-mode-conversion model in both deterministic and probabilistic fracture mechanics analyses will be validated by testing of cruciform specimens (plate and weld material) in the transition region. The majority of the tests will be conducted at temperatures such that the failure mode is predominantly cleavage with some prior ductile tearing that is prototypic of RPV behavior.

3.3.4.3.1 Validation Testing (Subtask 4.3.D) The cruciform validation tests (which include pre-cleavage ductile tearing) will be carried out (under Task 3) utilizing the test matrix defined in FY 1996 detailing:

(a) specimen type,
(b) crack geometry,
(c) and test temperatures and loading conditions.

The experimental data from these specimens will provide input for the assessment of the developed fracture-mode-conversion model for the ductile-to-brittle transition temperature region.

3.3.4.3.2 Predictive Capabilities (Subtask 4.3.E) Posttest analyses will be performed with FAVOR to confirm the predictive capabilities of the method 'ogy. Modifications will be made to the predictive engineering methodology based on validation test results.

3.3.4.3.3 Reports (Subtask 4.3.F) A NUREG/CR report describing the methodology for inclusion of fracture-mode-conversion model in deterministic and probabilistic fracture mechanics analyses will be issued upon completion of this Subtask.

3.3.5 Fracture Analysis Methods Development and Applications (Task 5)

3.3.5.1 Continuing Development of FAVOR (Subtask 5.1) During FY 97, the correlation to include clad plasticity (developed in Task 3.1) will be incorporated into FAVOR. The methodology to incorporate "plant-specific" vessel inspection data into "method 2" PTS PFM analyses will be implemented into FAVOR. The flaw density and flaw size distribution data generated by PRODIGAL expert system will be considered as the prior distribution. "Plant specific" flaw inspection data will be incorporated through Bayesian updating to generate plant-specific posterior flaw density and flaw size distributions. Personnel from Sandia National Labortaory will be responsible for the development of Bayesian updating techniques. In order to meet the milestone for the implementation of Bayesian updating techniques into FAVOR, the methodology developed by Sandia must be received during the first quarter of FY 97.

3.3.5.2.b PHASE II: Demonstration Analysis: Integration and Application of Revised Technical Bases and Methodologies to Plant Specific Test Case (Subtask 5.2.b) The objective of Phase II is to perform demonstration analyses for PTS analysis methods 1 and 2 for two seperate nuclear plants. Phase II will be a coordinated effort between various organizations to integrate and apply the revised technical bases and methodologies, previously developed in subtask 5.2.a, to plant-specific test cases using both method 1 and method 2 types of PTS PFM analysis.

The first plant has been designated as the H.B. Robinson plant. The second and plant will be designated by the NRC at the appropriate time. During FY 97, demonstration PTS PFM analyses will be performed for the H.B. Robinson plant and plant number 2. During FY 97, a NUREG will be produced that describes the technical bases for the analyses and the results of the H.B. Robinson test cases analyses. This task will provide input to the NRC for producing a NUREG letter describing PTS PFM analyses results for unit 2. INEL will provide all transient definition data (thermal-hydraulic boundary conditions) to this subtask. The original dates for receipt of the thermal hydraulic boundary conditions are given in section 13, Addendum to the 189.

3.3.5.3 Provide Technical Support for NRC (a) This subtask provides for technical support to the NRC staff during ACRS /CRGR reviews and public comment period. (b) This subtask provides continuing technical support to the NRC staff in computational benchmark and specialists / experts meetings.

3.3.7 Integration of Results into a State-of-the-Art Analysis Methodology (Task 7)

The objective of this task continues to be the evaluation, interpretation, and application of the results of HSST Program research to the regulatory process through interpretive reports, consulting to the NRC, and direct participation in the consensus codes and standards process. The NRC has elected to base its regulation of the nuclear power industry, as much as possible, on industry consensus codes and standards, making direct participation in the development of these standards an activity of prime importance. During FY 1997, significant additional research results will become available from Tasks 2, 3, and 4, including fracture toughness data from medium sized and large clad cruciform beam specimens containing shallow, finite-length, surface cracks, refined constraint analyses, further developments of a clad yielding computational model and developments for a predictive computational model of

ductile-to-cleavage mode conversion. These results will be used to further develop the basis for a comprehensive fracture analysis methodology for reactor pressure vessels. During FY 1997, successful balloting and initial publication of an ASTM standard for establishing fracture toughness values in the transition range, based on small-specimen test data, are anticipated. The descriptions and titles of the Subtasks in Task 7 will remain the same as for FY 1996. A NUREG report describing preliminary logic for a comprehensive fracture analysis methodology for clad, biaxially loaded, reactor pressure vessels, based on experimental data for 2-D and 3-D flaws and analyses considering clad yielding, constraint effects, residual stresses and stable crack growth below the upper shelf, will be issued in early FY 1997. Meeting reports documenting business conducted at consensus codes and standards meetings will be transmitted to the NRC Project Manager within a month after the meetings.

3.4 FY 1998

3.4.1 Program Management (Task 1)

The program direction, monitoring and control, subcontract management, quality control, and communications activities defined in sections 3.1.1 and 3.2.1, will be continued in FY 1998. Special emphasis will be placed on reviewing the implementing procedures used in Task 7 to integrate the program research results into a comprehensive pressure-vessel-integrity-assessment methodology.

3.4.5 Fracture Analysis Methods Development and Applications (Task 5)

3.4.5.1 Continuing Development of FAVOR (Subtask 5.1) During FY 98, the correlation to include fracture mode conversion (developed in Task 4.3) will be incorporated into FAVOR.

During FY 98, work will be initiated on developing a new user guide for FAVOR, in anticipation of releasing the latest version of the code to commercial and research organizations active in safety analyses of RPVs. This user guide will provide technical explanations and example problems for both methods 1 and 2 types of PTS PFM analyses.

During FY 98, the latest version of the FAVOR code for performing both method 1 and method 2 type of PTS analyses will be released to commercial and research organizations active in RPV safety analyses.

3.4.5.2 PTS Applications (Subtask 5.2)

3.4.5.2.d Impact Analysis Of Proposed Revisions To Regulatory Guide 1.154 (Subtask 5.2.d) During FY 98, a value and impact analysis of proposed revisions to Regulatory Guide 1.154 will be performed. This impact analysis is similar in scope to NUREG / CR 5186 on the low-temperature over-protection issue in RPVs.

3.4.5.3 Provide Technical Support for NRC (Subtask 5.3) (a) This subtask provides for technical support to the NRC staff during ACRS /CRGR reviews and public comment period, (b) This subtask provides continuing technical support to the NRC staff in computational benchmark and specialists / experts meetings.

3.4.7 Integration of Results Into a State-of-the-Art Analysis Methodology (Task 7)

At the beginning of FY 1998, all the other technical tasks in the HSST Program will be either complete or will merge with Task 7. The objective of Task 7, in FY 1998, will be a final evaluation, interpretation, and incorporation of HSST Program research results into a comprehensive fracture analysis methodology for reactor pressure vessels. The emphasis on transferring HSST Program research results into consensus codes and standards will remain unchanged. Significant new research results from FY 1997, including additional unclad cruciform specimen data for 2-D flaws and clad cruciform data for 3-D flaws, a final validated constraint methodology, final clad yield and mode-conversion analysis procedures, J-R data for A302-B (mod.) steel, additional high-rate dynamic initiation fracture toughness data, a complete set of stress-intensity-factor influence

coefficients for a wide range of a/W and $7 \le R_i/t \le 20$, and several improvements in PTS analysis procedures will be available for incorporation into the comprehensive fracture analysis methodology. A letter report describing updated logic for a comprehensive fracture analysis methodology for clad, biaxially loaded, reactor pressure vessels, based on experimental data for 2-D and 3-D flaws and analyses considering clad yielding, constraint effects, residual stresses and stable crack growth below the upper shelf will be issued in early FY 1998. Meeting reports documenting business conducted at consensus codes and standards meetings will be transmitted to the NRC Project Manager within a month after the meetings.

3.5 FY 1999 (10/1/98–12/31/98)

3.5.1 Program Management (Task 1)

The program direction, monitoring and control, subcontract management, quality control, and communications activities defined in sections 3.1.1 and 3.2.1, will be continued in first three months FY 1999, which are included in the period of performance for this 189. Discussions will be held with NRC to, (a) review the results obtained from the research program, and (b) provide assistance in the transfer and implementation of the comprehensive pressure-vessel-integrity-assessment methodology developed in Task 7 of the program.

3.5.7 Integration of Results Into a State-of-the-Art Analysis Methodology (Task 7)

The objective of Task 7 in the first three months of FY 1999 will be completion of the final evaluation, interpretation, and incorporation of HSST Program research results into a comprehensive fracture analysis methodology for reactor pressure vessels. The emphasis on transferring HSST Program research results into consensus codes and standards will remain unchanged. A NUREG report describing the completed comprehensive fracture analysis methodology for clad, biaxially loaded, reactor pressure vessels, based on experimental data for 2-D and 3-D flaws and analyses considering clad yielding, constraint effects, residual stresses and stable crack growth below the upper shelf will be issued. Meeting reports documenting business conducted at consensus codes and standards meetings will be transmitted to the NRC Project Manager within a month after the meetings.

4. PROPOSED PERSONNEL:

The following personnel are proposed to execute the HSST program scope of work in the performance period covered by this 189.

Task	Personnel	Proposed Assignment
H.1	W. E. Pennell	Program Manager
H.2	B. R. Bass	Task Leader/lead investigator
H.3	W. J. McAfee	Task Leader/lead investigator
H.2 & H.3	J. W. Bryson	Structural analysis
H.4	J. A. Keeney	Task Leader/lead investigator
H.5	T. L. Dickson	Task Leader/lead investigator
H.6	R. K. Nanstad	Task Leader/lead investigator
H.6 & H.7	D. E. McCabe	Metallurgy and experimental fracture mechanics
H.7	J. G. Merkle	Task Leader/lead investigator

Résumés for each of the individuals listed above are provided on the following pages.

Résumé

William E. Pennell
Engineering Technology Division
Oak Ridge National Laboratory

Education:

M.S.. Mechanical Engineering - 1958 Cranfield Institute of Technology, (UK)

Experience:

Structural Integrity Research - 6 years: Oak Ridge National Laboratory. Manager of the Heavy Section Steel Technology program. Development of fracture mechanics technology for application in the safety assessment of nuclear reactor pressure vessels (RPVs) containing flaws.

Nuclear Reactor Engineering - 25 years: Rolls Royce and Associates (UK) - 4 years. Manager of the Stress Office. Stress analysis of systems and components for naval reactors. **Westinghouse Electric Corporation - 20 years.** Manager of stress analysis for the Fast Flux Test Facility (FFTF) with responsibility for, (1) structural analysis and testing of reactor structures and components, (2) development and design application of high-temperature design criteria, and (3) development and application irradiation-induced swelling-and-creep-effects analysis methods. Manager of the reactor pressure vessel (RPV) contract for the FFTF Project. Manager of Reactor Engineering for the Clinch River Breeder Reactor Project (CRBRP), with responsibility for the reactor vessel, reactor internal structures, control rod system, head access area and reactor cavity equipment, stress analysis, and thermal-hydraulic analysis and testing. Manager of the CRBRP Seismic Task Force and the Pressurized Water Reactor Pre-Heat Steam Generator Task Force. Appointed Chief Engineer to the Westinghouse Advanced Energy Systems Division in 1984. **Tennessee Valley Authority - 1 year.** Manager of Engineering and Technical Services. Responsible for directing the work of the Nuclear, Electrical, Civil, and Mechanical Branches in the nuclear power recovery program.

Aircraft Structural Engineering - 5 years: Westland Aircraft (UK), A. V. Roe (UK), and Boeing Vertol. Stress analysis of aircraft structures.

Technical Society, University, and International Activities

Invited lecturer at the Massachusetts Institute of Technology Nuclear Power Reactor Safety course, 1974, 1975, and 1976. Member of the American Society of Mechanical Engineers (ASME). Member of the ASME Section XI Working Group on Operating Plant Criteria. Session developer and editor of proceedings volumes for the ASME Pressure Vessel and Piping Division conferences in 1991, 1992, and 1993. Member of numerous DOE and NRC international reactor technology exchange teams.

Patents, Publications and Presentations

Nine U.S. patents for fast breeder reactor inventions. Numerous papers and presentations on nuclear reactor design and safety topics. ORNL Showcase Presentation, "Structural Integrity of Irradiated RPVs," in 1991.

Awards

Westinghouse corporate Special Award for Exceptional Achievement in 1977 for management of the FFTF Seismic Task Force, and in 1983 for management of the Steam Generator Task Force.
Martin Marietta Energy Systems Technical Achievement (1989) and Management (1993) awards.
ASME Pressure Vessel and Piping Division award for the Outstanding Survey Paper of 1992.

Résumé

B. Richard Bass
Computing Applications Division
Oak Ridge National Laboratory (ORNL)

Education:

B.S.	Mechanical Engineering	1964	Tulane University
	Additional Undergraduate study in Mechanical Engineering		Manchester University, U. K..
Ph.D.	Mechanical Engineering	1969	Tulane University

Employment and Experience:

Dr. Bass served as an Assistant Professor of Engineering Mechanics at Old Dominion University (ODU), Norfolk, Virginia, from 1969 to 1975. His research and teaching efforts were concentrated in the areas of rational mechanics and computational continuum mechanics. While at ODU, he was awarded, as principal investigator, a National Science Foundation research grant in the area of thermodynamic stability theory. During academic year 1975–1976, Bass held a visiting faculty appointment at the University of Wales, Swansea, where he engaged in research in finite element applications to thermally-loaded structures.

Since 1977, Dr. Bass has played a major role in the pre-test planning and post-test analysis of large-scale testing in the NRC-sponsored Heavy-Section Steel Technology (HSST) Program at ORNL. He presently serves as the leader of the task investigating cladding effects within the HSST program. As a part of these efforts, he has published more than 50 technical papers and reports. He is widely recognized by his peers as an expert in analytical mechanics, especially relative to fracture analysis methods. In his leadership role for the cladding effects task, he coordinates the work of researchers within ORNL and also monitors the technical work of program subcontractors. He has served as the HSST technical monitor for the joint Japan/U.S. Program for Elastic-Plastic Fracture in Inhomogeneous Materials and Structures (EPI).

International Activities:

In addition to the international activities cited above, Dr. Bass' expertise in analysis methods developments led him to play a key role in the international FALSIRE (Fracture Analysis of Large-Scale International Reference Experiments) project. Project FALSIRE was sponsored by the Fracture Assessment Group of Principal Working Group Number 3 (PWG/3) of the Organization for Economic Cooperation and Development (OCED)/Nuclear Energy Agency's (NEA's) Committee on the Safety of Nuclear Installations (CSNI). He served as a co-organizer of a three-day workshop on Project FALSIRE held during May 1990, and he also served as senior author of a comprehensive report of the findings, conclusions, and recommendations of that workshop. That report was completed in 1992 as a cooperative effort between Gesellschaft fur Reaktorsicherheit and ORNL.

Recently, Dr. Bass served as a co-organizer of an international conference entitled International Specialists' Meeting on Fracture Mechanics Verification by Large-Scale Testing. The conference was sponsored by the IAEA International Working Group of Life Management of Nuclear Power Plants and OECD/NEA-CSNI'S Fracture Assessment Group.

Résumé
Wallace J. McAfee
Engineering Technology Division
Oak Ridge National Laboratory

Education:

B. S. Mathematics	1959–962	Union University, Jackson, Tennessee
B. S. Mechanical Engineering	1962–1964	University of Tennessee, Knoxville, Tennessee
M. S. Engineering Mechanics	1969	University of Tennessee, Knoxville, Tennessee
Ph. D. Engineering Mechanics	1970	University of Tennessee, Knoxville, Tennessee

Employment History:

Oak Ridge National Laboratory	1989–present	Engineering Technology Division
Westinghouse Electric Corporation	1983–1989	Nuclear Components Division
Oak Ridge National Laboratory	1970–1978	Engineering Technology Division
Oak Ridge National Laboratory	1966–1967	Engineering Technology Division

Professional Experience:

Wallace (Wally) McAfee received B. S. degrees in both mathematics and mechanical engineering. He then entered the University of Tennessee Graduate School of Engineering to study for advanced degrees in Engineering Mechanics. He took a break in his graduate studies to work at the Oak Ridge National Laboratory (ORNL) from 1966 to 1967 where he worked to develop and make operational a three-dimensional scattered-light polariscope for analysis of through-wall stresses in photoelastic models of critical regions of prestressed concrete reactor pressure vessels. Returning to graduate school in 1967, he adapted the scatter-light technique to the experimental analysis of three-dimensional laminar flow problems. For the experimental techniques developed, he and his major professor were presented the M. Hetenyi Award for the outstanding research paper of the year, Society of Experimental Stress Analysis, 1971. Completing graduate work, he returned to ORNL where, over the next 14 years, he worked on a wide range of projects the central focus being the development and verification of procedures and criteria for use in the design and analysis of pressure or containment systems (water, -gas-, sodium-cooled reactors, fusion devices, and geothermal plants). In 1983, Wally accepted a position at the Westinghouse Nuclear Components Division (WNCD) as a lead engineer on fabrication and analysis of an advanced sodium-cooled steam generator. For his work on developing a radiographic acceptance criteria for tube-to-tube sheet welds, he was awarded an WNCD Quality Achievement Award. While at WNCD, he also served as lead analyst on several special projects for commercial reactors, spent fuel storage facilities, and defense products. Wally returned to ORNL in 1989 and assumed the task as program manager for the Jo-Block Clad Evaluation Program and the Warm Prestress Beam Program, both sponsored by Knolls Atomic Power Laboratory. After completion of these programs, he became a member of the ORNL HSST Program staff with primary responsibilities for experimental support for the HSST Program. In this position, he had primary responsibility for designing, constructing, and bringing to operational status the HSST biaxial beam test facility.

Publications:

Besides the Masters thesis and Ph.D. dissertation, Wally has authored or co-authored 20 technical reports and 12 journal articles dealing with diverse topics such as experimental analysis of fluid flow, experimental stress analysis using both conventional strain gages and photoelastic techniques, time-dependent and -independent materials behavior, development of design codes and standards, and fracture mechanics.

Professional Societies:

Member of American Society of Mechanical Engineers

Résumé

John W. Bryson, Jr.
Engineering Technology Division
Oak Ridge National Laboratory

Education:

B. A.	Chemistry	1964–1967	University of the South, Sewanee, Tennessee
B. S.	Chemical Eng..	1967–1969	Columbia University, New York, New York
M. S.	Eng.. Mechanics	1970–1975	University of Tennessee, Knoxville, Tennessee
Completed coursework toward PhD Eng.. Mech.		1975–1978	University of Tennessee, Knoxville, Tennessee

Employment:

Oak Ridge National Lab.	1969–present	Engineering Technology Division

Experience:

John Bryson has over 25-years' experience in structural mechanics, specializing in computational fracture mechanics. He has served as an analyst on the ORNL Nozzles and Piping Program, the ORNL-KAPL Navy Program, and most recently, the ORNL Heavy Section Steel Technology Program.

Publications:

John has authored or co-authored over 40 technical papers and reports.

Résumé

Janis A. Keeney
Computing Applications Division – Structural and Fracture Mechanics Group
Oak Ridge National Laboratory

Education:

B.S. Chemical Engineering	1981–1984	University of Tennessee, Knoxville, Tennessee
M.S. Engineering Science & Mechanics	1987–1990	University of Tennessee, Knoxville, Tennessee
Westinghouse Technology Course (R-101P)	1992	USNRC Technical Training Center

Employment History:

Oak Ridge National Laboratory	1984–present	Computing Applications Division

Experience:

Janis Keeney has over ten-years' professional experience in computational fracture mechanics (CFM). The majority of her technical responsibilities are in support of the Heavy-Section Steel Technology (HSST) Program (sponsored by the NRC) which is an engineering research activity devoted to extending and developing the technology for assessing the margin of safety against fracture of reactor pressure vessels (RPVs). Janis has been a Task leader for five years (in the areas of cladding effects and precleavage ductile tearing) and supports three other Tasks through development and implementation of CFM analysis techniques with applications for experimental pretest planning and posttest analysis of heavy-section experiments.

Work outside the HSST Program includes computational support for RPV International Programs (CFM analysis of international experiments) and for Y-12 Development (modeling quench thermal boundary conditions). Janis has participated in developing several of the HSST fracture analysis codes utilized by a number of other R&D institutions in the United States and western Europe.

Janis has experience in several facets of structural mechanics analysis techniques (two- and three-dimensional, linear and nonlinear, static and dynamic finite-element analysis) used for heat conduction and stress analysis of RPVs under pressurized-thermal-shock loading, and dynamic crack propagation in cylinders and plates. She also has a working knowledge of PCs (Mac and IBM) and workstations.

Publications and Presentations:

Author/co-author of over 94 technical papers and ORNL reports with over 250 citations, and have made 23 national and international technical presentations.

Professional Societies and Awards:

Active member on Subcommittee E8.08 on Elastic-Plastic Fracture Mechanics Technology of the American Society for Testing Materials, member of American Society of Mechanical Engineers and Tau Beta Pi (Engineering Honor Society)

Significant Achievement Award from Martin Marietta Energy Systems, Inc. (November 1992)

Résumé

Terry L. Dickson
Computing Applications Division
Computational Engineering Section
Oak Ridge National Laboratory

Education:

B.S. Mechanical Engineering	1973	Memphis State University, Memphis, Tennessee
M.S. Engineering Science and Mechanics	1978	University of Tennessee, Knoxville, Tennessee
Several continuing education and professional courses	1978–present	

Employment History:

Oak Ridge National Laboratory	1988–present
Arabian American Oil Company	1980–1988
Tennessee Valley Authority	1973–1980

Professional experience:

Terry Dickson worked for TVA from 1973–1980. From 1973–1978, his primary responsibilities were in the development and application of thermal-hydraulic and structural mechanics simulation software for the design and operation of fossil and nuclear power plants. During this period, he completed a graduate degree at evening school. From 1978–1980, he worked as a results engineer at a 2600 Mw fossil power plant where his primary responsibilities were monitoring and improving plant efficiency and the balancing of large rotating machinery.

From 1980–1988, Terry worked for the Arabian American Oil Company in Dhahran, Saudi Arabia. From 1980–1986, his primary responsibility was the development of oil field fluid flow simulation software. Terry designed and taught courses to the Arabian petroleum engineering community in the application of surface facility and reservoir simulators. During 1986–1988, Terry was supervisor over a group of geophysicists and systems analysts whose responsibilities included developing well log processing software systems and the development and maintenance of databases which stored millions of records containing hydrocarbon fluid property data obtained from core samples.

Since 1988, Mr. Dickson has been working at Oak Ridge National Laboratory in support of the Heavy Section Steel Technology Program. His primary responsibilities have been in the development and application of simulation software for performing structural integrity analyses of nuclear reactor pressure vessels. He has authored several technical papers and reports and made several technical presentations.

Résumé

Randy K. Nanstad
Metals and Ceramics Division
Oak Ridge National Laboratory

Education:

B.S. Engineering,	1960–1964,	U.S. Military Academy, West Point, New York
M.S. Nuclear Engineering,	1969–1971,	University of Wisconsin, Madison, Wisconsin
Ph.D. Metallurgical Engineering,	1971–1974,	University of Wisconsin, Madison, Wisconsin

Employment History:

U.S. Army,	1964–1969	
Oak Ridge National Laboratory,	1974–present	Metals and Ceramics Division

Professional Experience:

As Leader of the Fracture Mechanics Group, Metals and, ORNL, Nanstad is charged with the investigation of materials behavior in structural applications, particularly fracture properties and relationships to microstructure and radiation effects.

Experimental fracture mechanics with emphasis on elastic-plastic behavior, to provide techniques for characterizing material parameters critical to the fracture process.

Fracture studies of low-alloy pressure vessel steels to provide engineering data for structural integrity assessments of nuclear reactor vessels, coal conversion pressure vessels, etc., including statistical evaluation.

Assessment of prestressed concrete for design of pressure vessels for high-temperature nuclear and fossil energy applications.

Irradiation studies of low-alloy steels and stainless steels to determine effects of neutron irradiation on mechanical properties and fracture toughness of light-water nuclear reactors.

Served as one of three primary members for evaluation of High-Flux Isotope Reactor pressure vessel embrittlement situation.

Special Assignment, Program Manager, NRC Licensing Assistance Program, Materials and Mechanical Engineering.

Publications:

75

Professional Societies:

ASM International American Society for Testing and Materials American Welding Society

Résumé
Donald E. McCabe
Metals and Ceramics Division
Oak Ridge National Laboratory

Education:

B.S. Metallurgical Engineering	1951–1957	University of Wisconsin, Madison, Wisconsin
Graduate Studies	1958–1960	University of Cincinnati, Cincinnati, Ohio
Fracture Mechanics Workshop	1954	Denver , Colorado

Employment History:

Armco Steel Corp.	1957–1976	Research Laboratory, Middletown, Ohio
Westinghouse Electric Corp.	1976–1985	Research and Development Center, Pittsburgh, Pennsylvania
Materials Engineering Associates	1985–1989	Lanham, Maryland
Oak Ridge National Laboratory	1989–present	Metals and Ceramics Division

Professional Experience:

Don McCabe's work at Armco Steel Corp. involved principally drawability studies on low-carbon steel sheet materials. Other activities included hydrogen diffusion experiments, metallurgy of stainless steels, tensile testing and work-hardening models, fracture mechanics test method development, fatigue, stress-corrosion cracking, and probabilistic fracture mechanics. His work at Westinghouse involved the use of elastic-plastic fracture mechanics methods and the application of the technology to practical engineering problems. At Materials Engineering Associates, Don's work included consulting and leading research projects under contract agreements. At Oak Ridge National Laboratory, Don is involved in testing nuclear reactor pressure vessel steels and weldments. He is also participating in committee collaborations and writing American Society for Testing and Materials standards.

Publications:

40

Professional Societies:

ASM International
American Society for Testing and Materials
Professional Engineer, State of Pennsylvania

Résumé
John Graham Merkle
Engineering Technology Division
Oak Ridge National Laboratory

Education:

	Degree	Area	Institution	Date
Education: 6-1/2				
Military Service: 3	BCE	Civil Engineering	Cornell University	1957
Design and Applied Research: 32-1/2	MCE	Civil Engineering	Cornell University	1962

Professional Experience:

Mr. Merkle received his bachelor's and master's degrees in civil engineering from Cornell University in 1957 and 1962, respectively. While a graduate student at Cornell, he taught the undergraduate laboratory course in soil mechanics for civil engineers. During the intervening years, he was a commissioned officer in the U.S. Navy Civil Engineering Corps and, in 1962, he joined ORNL. In 1963 he joined the Applied Mechanics Section in the Reactor Division and is now a member of the Engineering Mechanics and Structures Section in the Engineering Technology Division. Since its inception in 1967, he has been a major contributor to the Heavy-Section Steel Technology (HSST) Program, which has provided fracture mechanics analysis methods and experimental data used worldwide in the development of fracture safety standards for nuclear pressure vessels. He has also served on professional committees of the American Society of Mechanical Engineers, American Society for Testing and Materials (ASTM), and the Pressure Vessel Research Committee. In addition, he has served as a consultant to the Advisory Committee on Reactor Safeguards, the U.S. Department of Energy, and the U.S. Nuclear Regulatory Commission, which sponsors the HSST Programs.

Present Position: Research Specialist, Engineering Mechanics and Structures Section, Engineering Technology Division, Oak Ridge National Laboratory.

Publications:

Over 90 journal articles, laboratory reports, and other publications

Professional Societies:

Member, American Society of Civil Engineers

Professional Committee Appointments:

- ASME Section XI Working Group on Pipe Flaw Evaluation, Working Group on Flaw Evaluation, and Subgroup on Evaluation Standards
- ASTM Committee E-08 on Fatigue and Fracture, Company Representative: Co-chairman of Task Group 08.08.03 on Ductile-to-Brittle Transition Regime
- PVRC Ad Hoc Task Group on Fracture Toughness Requirements for Ferritic Materials
- PVRC/MPC Working Group on Crack Arrest Analysis and Test Methods

Awards:

- ASTM Committee E-24 Irwin Award for leadership in the development of elastic-plastic fracture mechanics
- Martin Marietta Technical Achievement Award for fracture mechanics evaluation of the High Flux Isotope (HFIR) pressure vessel
- Invited to present the Fifth Annual Swedlow Memorial Lecture at the 26th National Symposium on Fracture Mechanics

5. MEETINGS/TRAVEL:

5.1 FY 1995

To meet the objectives of this project, funds for foreign and domestic travel have been specified. Foreign travel to Sweden, Belgium, Germany, Switzerland, France, United Kingdom, Japan, and Brazil scheduled in the FY 1995, 1996, 1997, and 1998 performance period for the conduct of project business.

Location	Purpose	H.1	H.2	H.3	H.4	H.5	H.6	H.7
		Number of trips planned for each task in 1995						
(a) Foreign Travel								
Stockholm-Sweden, Renerdiers-France Freigurg-Germany, Risley-England	Visit to the Royal Institute of Technology-Stockholm, Franhofer Institute-Freiburg, Electricite de France-Renardiers, and AEA, Technology-Risley. The purpose of these visits is an exchange of information on reactor pressure vessel structural integrity and irradiation embrittlement research	1						
Takasago-Japan, Muroran-Japan, Toyohashi-Japan, Tokyo, Japan.	Fracture technology exchange with Mitsibushi Heavy Industries-Takasago, Japan; Steel Works-Muroran.; Toyohashi University-Toyohashi; University of Tokyo and the Tokyo Institute of Technology.		1					
Porto Alegre-Brazil	Present papers from the HSST program at the 1995 SMiRT conference in Brazil			1				
(b) Domestic Travel								
Williamsburg, VA	ASTM 27th National Symposium on Fracture			1	1			1
Honolulu, HI	ASME PVP conference	1				1		
San Antonio, TX	ASME Section XI committee meetings							2
Anchorage, AL	ASME Section XI committee meetings							1
Chicago, IL	ASME Section XI committee meetings							2
San Francisco, CA	ASME Section XI committee meetings							2
Denver, CO	ASTM committee E08 meeting			1				1
Norfolk, VA	ASTM committee E08 meeting			1				1

(b) Domestic Travel (continued)

Number of trips planned for each task in 1995

Location	Purpose	H.1	H.2	H.3	H.4	H.5	H.6	H.7
Bethesda, MD	NRC Water Reactor Safety meeting	1	1					
Rockville, MD	HSST program discussions and consultations with the NRC HSST Program Monitor plus interaction with NIST	3				2		
Dynamic Fracture Toughness at the Naval Surface Warfare Center Caderock Division	Readiness review and progress review for the dynamic fracture toughness testing program.		1				4	
Location yet to be determined	ASTM Task Group E08-08.03 Working Group meetings (2)							2
Rockville, MD	Presentation and discussion of results from the A302 B ductile tearing test program.						2	
Location yet to be determined	PTS analysis methods bench-marking evaluation.					2		
Location yet to be determined	Interaction/coordination meetings for participants in Reg. Guide 1.154 revision project.					2		
Seattle, WA	Co-Chair the session on Safety and Pressure Vessel Integrity at the ANS conference on Safety of Operating Reactors.	1						
Gaithersburg, MD	Discussions with NIST on the clad beam testing subcontract.			3				
Fabrication and test service vendors. Location yet to be determined	Discuss fabrication and test requirements, perform QA checks and witness tests.		3	2				
Rockville, MD	NRC-sponsored workshop on constraint effects in fracture	1	1	1				
Location yet to be determined	ACRS and Regulatory authority briefings on fracture technology developments from the HSST program.		1					

5.2 FY 1996

Location	Purpose	H.1	H.2	H.3	H.4	H.5	H.6	H.7
		Number of trips planned for each task in 1996						
(a) Foreign Travel								
Specific laboratories to be visited yet to be determined	Research program coordination and fracture technology interchange with European and Japanese fracture technology research and development laboratories	1						
Nuclear Research Laboratories, REZ Czech Republic	Working meeting for the interchange of information from the U.S. and Czech biaxial shallow-flaw fracture-toughness test programs. The U.S. and Czech programs use identical test specimens and loading fixtures and therefore produce comparable test results.		1					
Fraunhofer Institute Fur Werkstoff Mechanik change (IWM) Freiburg, Germany and Bundesanstalt für Material forschung undprüfung (BAM) Berlin, Germany	Working meeting for the inter- of information from the U.S. and German fracture-toughness-constraint-effects programs with special emphasis on the effects of finite-length flaws, cladding, and stress biaxiality.			1				
(b) Domestic Travel								
Location yet to be determined	ASTM 28th National Symposium on Fracture			1	1			
New Orleans, LA	ICON-4 Conference	1		1				
Location yet to be determined	ASME Section XI Committee Meetings							8
Location yet to be determined	ASTM Committee E08 Meetings			2				2
Rockville, MD	NRC Water Reactor Safety Meeting	1	1					
Rockville, MD	HSST program discussions and consultations with the NRC HSST Project Manager	3				2		
Location yet to be determined	ASTM Task Group E08-08.03 Working Group meetings							2

(b) Domestic Travel (continued)

Location	Purpose	Number of trips planned for each task in 1996 H.1	H.2	H.3	H.4	H.5	H.6	H.7
Rockville, MD	PTS analysis methods and Reg. Guide 1.154 revision project					1		
Sandia National Lab Albuquerque, NM	Interaction/coordination meetings for participants in the Reg. Guide 1.154 revision project					1		
Fabrication service vendors. Location yet to be determined	Discuss fabrication requirements and perform QA checks.		3	2				
Location yet to be determined	ACRS and regulatory authority briefings on fracture technology developments from the HSST program as directed by NRC.	1						

5.3 FY 1997

Location	Purpose	Number of trips planned for each task in 1997 H.1	H.2	H.3	H.4	H.5	H.7
(a) Foreign Travel							
SMiRT Conference Location yet to be determined	Present papers from the HSST program at the 14th SMiRT conference.			1			
AEA Technology in Risley, United Kingdon, and Materialprüfungsanstal Universität Stuttgart, Germany	Give an invited presentation on HSST Program research at the U.K. Health & Safety Executive Structural Integrity Seminar, and attend the MPA Seminar.	1					
Staatliche Materialprüfungsanstalt Universität Stuttgart (MPA), Stuttgart, Germany	Interchange of information on thermal shock testing of cylinders and vessels.		1				
(b) Domestic Travel							
Location yet to be determined	ASTM 29th National Symposium on Fracture			1	1		
Location yet to be determined	ASME PVP Conference	1				1	
Location yet to be determined	ASME Section XI Committee meetings						8

(b) Domestic Travel (continued)

Location	Purpose	Number of trips planned for each task in 1997 H.1	H.2	H.3	H.4	H.5	H.7
Location yet to be determined	ASTM Committee E08 meetings			2			2
Rockville, MD	NRC Water Reactor Safety program meeting	1	1				
Rockville, MD	HSST program dicsussion and consultations with the NRC HSST Project Manager	3				1	
Location yet to be determined	ASTM Task Group E08-08.03 Working Group meetings						2
Rockville, MD	PTS analysis methods and Reg. Guide 1.154 revision project					3	
Location yet to be determined	Discuss fabrication requirements and perform QA checks.		3	2			
Location yet to be determined	ACRS and regulatory authority briefings on fracture technology developments from the HSST program as directed by NRC.	1					

5.4 FY 1998

Location	Purpose	Number of trips planned for each task in 1998 H.1	H.7
(a) Foreign Travel			
Specific laboratories to be visited yet to be determined	**Research program coordination and fracture technology interchange with European and Japanese fracture technology research and development laboratories.**	1	
(b) Domestic Travel			
Location yet to be determined	**ASTM 30th National Symposium on Fracture**		2
Location yet to be determined	**ASME PVP Conference**	1	1
Location yet to be determined	**ASME Section XI Committee meetings**		8
Location yet to be determined	**ASTM Committee E08 meetings**		4
Rockville, MD	**NRC Water Reactor Safety program meeting**	1	

(b) Domestic Travel (continued)

Location	Purpose	Number of trips planned for each task in 1998 H.1	H.7
Rockville, MD	HSST program dicsussion and consultations with the NRC HSST Project Manager	3	
Location yet to be determined	ASTM Task Group E08-08.03 Working Group meetings		2
Location yet to be determined	ACRS and regulatory authority briefings on fracture technology developments from the HSST program as directed by NRC.	1	

5.5 FY 1999 (10/1/98-12/31/98)

Location	Purpose	Number of trips planned for each task in 1999 H.1	H.7
(a) Foreign Travel			
No foreign travel is planned for this period			
(b) Domestic Travel			
Location yet to be determined	ASME Section XI Committee meetings		2
Location yet to be determined	ASTM Committee E08 meetings		2
Rockville, MD	NRC Water Reactor Safety program meeting	1	
Rockville, MD	HSST program discussion and consultations with the NRC HSST Project Manager	3	

6. NRC FURNISHED MATERIALS:

Test specimens will be fabricated from NRC-owned material procured in earlier phases of the HSST program.

7. RELATIONSHIP TO OTHER PROJECTS:

The HSST Program is carried out in cooperation with many other research efforts sponsored by the federal government, private institutions, and industry. Close cooperation is maintained between the HSST and HSSI Programs at ORNL. Other ORNL programs related to the HSST program are the Nuclear Plant Aging Research, Nuclear Operations Analysis Center, RPV International Program Support, and the Structural Life Extension of Concrete Components. The HSST program is being carried out in close cooperation with industry-sponsored efforts that are coordinated by the Pressure Vessel Research Council. These include material-property studies, in-service weld-repair techniques, and nondestructive and in-service inspections methods and by-standing committee meetings, ad hoc meetings, and published reports. Additional cooperative efforts are maintained with the ASME, EPRI, ASTM, PVRC, IAEA, CSNI, and NRC-sponsored cooperative programs with foreign nuclear organizations involved in safety-related RPV research.

8. REPORTING REQUIREMENTS AND SCHEDULE:

FY 1994

A. **NUREG Reports:**

D. K. M. Shum, J. W. Bryson, and J. G. Merkle, *Potential Change in Flaw Geometry of an Initially Shallow Finite-Length Surface Flaw During a Pressurized-Thermal-Shock Transient*, NUREG/CR-5968 (ORNL/TM-12279), September 1993.

B. R. Bass, J. W. Bryson, T. J. Theiss, M. C. Rao, *Biaxial Loading and Shallow Flaw Effects on Crack-Tip Constraint and Fracture Toughness*, NUREG/CR-6132 (ORNL/TM-12498), January 1994.

C. W. Schwartz, *Crack-Speed Relations Inferred from Large Single-Edge-Notched Specimens of A533 B Steel*, NUREG/CR-5861, ORNL/SUB/79-7778/9, July, 1994.

W. E. Pennell, *HSST Semiannual Progress Report for October 1992-March 1993*, NUREG/CR-4219, ORNL/TM-9593/V10&N1, September 1994.

R. H. Dodds, Jr., *Constraint Effects on Fracture Initiation Loads in HSST Wide-Plate Tests*, NUREG/CR-6259, ORNL/TM-12796, UILU-ENG-94-2009, December 1994.

G. R. Irwin and X. J. Zhang, *Cleavage Behavior in Nuclear Vessel Steels*, NUREG/CR-6262, (ORNL/Sub/79-7778/11) Novmeber 1994.

J. A. Keeney, B. R. Bass, W. J. McAfee, S. K. Iskander, *Preliminary Assessment of the Fracture Behavior of Weld Material in Full-Thickness Clad Beams*, NUREG/CR-6228, ORNL/TM-12735, October 1994.

B. **Letter Reports:**

R. K. Nanstad, *Preliminary Review of Data Related to Inhomogeneity of Steels for Reactor Pressure Vessels*, NRC/LTR-93/36, December 1993.

T. L. Dickson, *Impact of Dynamic Crack Arrest on Fracture Analyses of Reactor Pressure Vessels Subjected to Pressurized Thermal Shock*, NRC/LTR-93/35, December 1993.

T. L. Dickson, *FAVOR Fracture Analysis of Vessels: Oak Ridge Release 9401 A Fracture Analysis Code for Nuclear Reactor Pressure Vessels*, January 1994.

J. A. Keeney, T. L. Dickson, *Stress-Intensity-Factor Influence Coefficients for Axially Oriented Semielliptical Inner-Surface Flaws in Clad Pressure Vessels ($R_i/t=10$)*, NRC/LTR-93/33, April 1994.

T. L. Dickson, J. W. Bryson, *Stress-Intensity-Factor Influence Coefficients for Circumferentially Oriented Semieliptical Inner-Surface Flaws in Clad Pressure Vessels ($R_i/t=10$)*, April 1994.

T. L. Dickson, *Impact of Dynamic Crack Arrest on Fracture Analyses of Reactor Pressure Vessels Subjected to Pressurized-Thermal-Shock*, ORNL/NRC/LTR-94/35, May 1994.

W. E. Pennell, et al., *Heavy-Section Steel Technology Program Monthly Management Report*, ORNL/HSST-MMR-94/1 through 12.

G. R. Irwin, X. J. Zhang and C. W. Schwartz, *Small Scale Non-Uniformities Related to Cleavage Initiation and Their Implications for Constraint Modeling*, ORNL/NRC/LTR-94/18, June 1994.

C. W. Schwartz, *Crack-Tip Loading Rates Preceding Cleavage Reinitiation*, ORNL/NRC/LTR-94/10, June 1994.

W. E. Pennell, Report on Foreign Travel of W. E. Pennell, Engineering Technology Division, ORNL/FTR-5102, August 1994.

FY 1995

A. **NUREG Reports:**

W. E. Pennell, et al., *Heavy-Section Steel Technology Program Semiannual Progress Report for April 1993–September 1993*, NUREG/CR-4219 (ORNL/TM-9593/V10&N2) May 1995.

W. E. Pennell, et al., *Heavy-Section Steel Technology Program Semiannual Progress Report for October 1993–March 1994*, NUREG/CR-4219 (ORNL/TM-9593/V11&N1), June 1995.

W. J. McAfee et al., *Biaxial Loading Effects on Fracture Toughness of Reactor Pressure Vessel Steel*, NUREG/CR-6273, (ORNL/TM-12866) November 1994.

J. A. Keeney, et al., *Assessment of the Fracture Behavior of Plate and Weld Material in Full-Thickness Clad Beams*, June 1995.

W. E. Pennell, et al., *Heavy-Section Steel Technology Program Semiannual Progress Report for April 1994–September 1994*, NUREG/CR-4219 (ORNL/TM-9593/V11&N2), September 1995.

W. E. Pennell, et al., *Heavy-Section Steel Technology Program Semiannual Progress Report for October 1994–March 1995*, NUREG/CR-4219 (ORNL/TM-9593/V12&N1), in publication.

D. E. McCabe, et al., *Effects of Specimen Size on J-R Curves for Multiple Heats of A 302 Grade B (Mod.) Steel*, September 1995.

Subcontractor, *Results of Dynamic Initiation Fracture Toughness Tests for A 533 Grade B Steel, HSST Plate 14*, September 1995.

B. **Letter Reports:**

W. E. Pennell, et al., *Heavy-Section Steel Technology Program–Monthly Management Reports*, ORNL/HSST-MMR-95/1 through 12.

J. A. Keeney, *Cleavage Fracture Analyses of the French Clad Beam Experiments– DSR3 and DD2*, October 1994.

D. J. Alexander and M. C. Rao, *Results of Metallurgical Investigations for Development of a Ductile-to-Brittle Fracture Mode Conversion Model*, March 1995.

W. E. Pennell and T. L. Dickson, *Preliminary Assessment of the Effects of Biaxial Loading on Reactor Pressure Vessel Structural-Integrity-Assessment Technology*, ORNL/NRC/LTR-95/3, March 1995.

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9. SUBCONTRACTOR/CONSULTANT AND MAJOR PROCUREMENT INFORMATION:

9.1 Subcontractor/Consultant Information

Subcontractor and consultant (S&C) support is used to make available to the program special facilities and talents not available at ORNL. S&C support is also used to supplement capabilities available at ORNL. All S&C support is performed in conformance with a Statement of Work (SOW) prepared each year for each of the S&C subcontracts. The SOW defines the scope of work to be performed for each of the program Tasks and defines the deliverables. The S&C work to be performed in the FY 1995-FY 1998 performance period, and the basis for selecting specific S&C subcontractors and consultants to perform that work, is summarized below. Note that the FY 1998 performance period ends in FY 1999, on 12/31/98.

9.1.1 FY 1995

Task Number	H.2	H.3	H.4	H.6	Totals
Subcontractor/Consultant	K$	K$	K$	K$	K$
Subcontractors					
University of Maryland	15	2	10		27
University of Illinois		17			17
National Institute of Standards and Technology		99			99
Naval Surface Warfare Center				140	140
Consultants					
Professor S. T. Rolfe		5			5
FY 1995 Totals	15	123	10	140	288

9.1.1.1 University of Maryland

A. Subcontract Work Package Scope and Objectives

Task 2: Metallurgical examinations of selected fracture surfaces from the biaxial fracture specimens tested in the load ratio development phase will be performed. Detailed examination of these fracture surfaces will be performed to determine and measure the location of initiation site(s). Further, the fracture surfaces will be sectioned at 90° to the flaw plane at a location near (within 2-3 mm) of the primary initiation site exposing in detail the cross-section of the surface. The exposed surface will be polished and etched, and measurements of the extent of the plastic zone size and the radius of the crack tip will be performed. This information will be used by ORNL, in conjunction with elastic-plastic finite-element analyses using a refined crack-tip model, to perform evaluations of a newly proposed strain-based dual-parameter fracture model. The results of these metallurgical examinations will be published in a letter report. Metallurgical examinations will also be made of fracture surfaces and sections from shallow-flaw fracture toughness specimens tested under uniaxial and biaxial loading in the verification phase. Fracture initiation sites will be located. The fracture initiation site information will be used by ORNL, together with elastic-plastic analysis of the crack-tip stress/strain field, to determine if crack initiation occurred in a location where the opening-mode stress was increasing with increasing applied load. This information will be used in the evaluation of stress-based dual parameter fracture toughness correlations. Sections cut at 90° to the fracture surface will be etched to reveal the size and configuration of the crack-tip plastic zone. This information will be used to validate and further develop a strain-based dual parameter fracture toughness correlation. Results from this work package will be included in a letter report.

Task 3: A three-dimensional elastic-plastic finite-element model of a finite-length surface flaw in a reactor pressure vessel will be generated. The model will be used to define the crack-tip stress and strain fields under pressurized-thermal-shock loading. Results from this analysis will be used, together with results from the ORNL analysis of the cruciform specimen, to determine the transferability of results from both stress-based and strain-based dual-parameter fracture toughness correlations. Results from the University of Maryland analysis will be documented in a letter report.

Task 4: Metallurgical examinations will be made of fracture surfaces from the full-thickness clad beam tests being conducted at NIST to (1) characterize the extent of crack-tip blunting prior to crack growth, (2) identify and characterize the microstructural features associated with microvoid formation and growth, and (3) identify and characterize the microstructural features responsible for mode conversion to cleavage. Results from these investigations will be used in the development of the fracture-mode conversion model. Results of the metallurgical examinations will be documented in a letter report.

B. Basis for Subcontractor Selection

The University of Maryland has unique experience relating to the fracture technology issues defined in the SOW. The University of Maryland team will include Professor G. Irwin, Professor W. Fourney, Professor G. Schwartz, and Research Assistant J. Zhang. Professors Irwin and Fourney are recognized worldwide as authorities on the development of fracture toughness correlations. They have extensive experience in integrating fracture test data, crack-tip stress-distribution analyses, and fractographic data to generate fracture toughness correlations, which are firmly based and widely used in the fracture-technology sections of national consensus Codes and Standards. Professor Schwartz has extensive experience in the application of advanced large-strain inelastic finite-element analysis methods to the analysis of crack-tip stress fields. Professor Schwartz has applied this expertise with outstanding success, in prior phases of this HSST subcontract, to evaluating the reponse of proposed dual-parameter fracture toughness correlations for prototypical reactor vessel geometric, loading, and constraint conditions. Research Assistant J. Zhang is a recognized authority on fractographic examination.

9.1.1.2 University of Illinois

A. Subcontract Work-Package Scope and Objectives

Task 4: Analysis of the ORNL shallow-flaw biaxial fracture toughness test has shown that (a) out-of-plane biaxial loading has a negligible effect on in-plane stresses at the crack tip, and (b) biaxial loading acts to restrict the growth of the crack-tip plastic zone. The analysis results indicate that crack-tip strains may play an important role in crack initiation. The Dodds-Anderson (D-A) stress-based fracture toughness scaling model can not predict the observed effects of biaxial loading on shallow-flaw fracture toughness.

The work to be performed in this subcontract will extend the D-A fracture toughness scaling model to include a stress-state-dependant fracture-initiation-strain criterion. The strain-based fracture-initiation criterion will be derived from plane-strain fracture ductility data generated by the HSST program in the FY 1994 performance period. The extended D-A scaling model will also include the pre-cleavage tearing model developed in the previous reporting period. A letter report will be produced documenting the development and validation of the extended D-A fracture toughness scaling model.

B. Basis for Subcontractor Selection

The principal investigator at the University of Illinois for this subcontract will be Professor R. Dodds. Professor R. Dodds is an internationally recognized authority on the effects of crack-tip constraint on fracture toughness. His research has included an investigation of the influence of pre-cleavage tearing on crack-tip constraint and failure-mode conversion. He has been successful in incorporating a modified form of the Gurson yield function into a finite-element program. He has used that program to simulate some of the structural response characteristics essential to a ductile-tearing crack-growth-analysis model. Professor Dodds is in a unique position

to rapidly develop and validate the ductile-tearing crack-propagation analysis capability required to support the ongoing HSST Program investigation of constraint effects in fracture.

9.1.1.3 National Institute of Standards and Technology (NIST)

A. Subcontract Work Package Scope and Objectives

Task 3: Three-point bend fracture toughness tests will be performed on three (3) full-thickness clad beam specimens taken from an RPV shell of a cancelled nuclear plant. These tests will be conducted in the 54 MN (12×10^6 lb) testing machine located at the NIST facilities in Gaithersburg, MD. Beam specimens having a 9 in. × 9 in. cross-section and containing a shallow through-clad notch will be provided to NIST by the HSST program. For each test, NIST will instrument the specimens, fatigue-sharpen the through-cracks, load the beams to failure, and provide the following information to ORNL: (1) calibration records; (2) temperature data; (3) test data; (4) test report; (5) specimen halves; (6) fracture surfaces; and (7) crack front irregularity measurements or photographs. This work is to be performed under existing interagency agreement with NIST, DE-AI05-92OR22034, extending through April 30, 1995.

B. Basis for Subcontractor Selection

NIST is uniquely suited for testing of the full-thickness clad-beam specimens required by the HSST program. The large tensile/compressive testing machine [12 million lb. (54 MN) in compression] located at NIST in Gaithersburg, MD, is one of the largest publicly available testing machines in the united states. Also, it is one of the few machines with the load capacity to test the size of specimen proposed in the workscope. In conjunction with this equipment capability, the researchers at NIST are highly experienced in large-scale testing, in data acquisition, and in post-test evaluations, as well as proper methods of preserving fracture surfaces to recover the maximum amount of data relevant to the fracture process. Researchers who will perform these tests have both national and international reputations in the field of fracture mechanics and represent an important resource for the interpretation of test results.

9.1.1.4 Battelle Memorial Institute (BMI), Columbus Division

The purpose of this work was, (a) to investigate field data on fractures in vessels and structures and determine if evidence exists for local brittle zones (LBZs) causing the failures, and (b) to develop and demonstrate a biaxial tension fracture-toughness test specimen based on a design developed and patented by BMI and others. The investigation of field data concluded that the available records were not sufficient to reveal any LBZ effects. Investigation of the biaxial-tension fracture-toughness test specimen design revealed that the minimum size for an acceptable test specimen was prohibitively large. Draft letter reports were produced and submitted to ORNL.

Work on this subcontract was completed in 1994. At the completion of the subcontract work, $15K of the assigned funding remained unspent. Recent contacts with BMI personnel have established that BMI has some unresolved claims on a portion of this unspent funding. These claims will be resolved when the DCAA audit of this subcontract is completed. The unspent balance must then be returned to NRC. The $15K obligation in FY 1995 is based upon the assumption that the DCAA audit of this subcontract will be completed in FY 1995.

9.1.1.5 Naval Surface Warfare Center, Carderock Division Detachment

A. Subcontract Work Package Scope and Objectives

Task 3: A testing program will be completed to obtain dynamic fracture initiation toughness (K_{Id}) data for a reactor pressure vessel steel as a function of loading rate and temperature. These data will be generated from compact tension (CT) specimens (up to 4T) fabricated from a plate of A533 Grade B Class 1 steel and tested at loading rates up to 10^5 MPa $\sqrt{m}$/s. The matrix defining the testing program includes 18 CT specimens that will be

fabricated from HSST Plate 14. Target loading conditions in the matrix were selected to confirm existing data and to extend the dataset to slightly higher loading rates. The Statement of Work (SOW) for this subcontract is defined in specification No. HSST-H06-94-001 Rev 1. The SOW provides detailed requirements for specimen fabrication, facilities preparation, test procedures, and documentation.

B. Basis for Subcontractor Selection

The HSST program for dynamic fracture toughness testing requires a high capacity testing machine capable of dynamically loading CT specimens up to four inches thick at loading rates up to 10^5 MPa $\sqrt{m}$/s. The Naval Surface Warfare Center, Carderock Division Detachment (NSWCC-DD) maintains a testing machine that meets these requirements. The NSWCC-DD has recently completed a series of dynamic-loading shakedown tests which confirmed that the machine is fully operational and capable of performing all of the tests defined in specification no. HSST-H06-94-001 Rev 1. The staff of NSWCC-DD has demonstrated expertise in fracture toughness testing. They have a thorough understanding of technical requirements of the dynamic fracture toughness testing program, and have the skills, experience, and equipment required to successfully complete the SOW defined in the test specification.

9.1.1.6 Professor S. T. Rolfe

A. Consulting Work Package Scope and Objectives

Task 2: Provide consultation and guidance to assist in development of the biaxial testing program for constant-depth (2-D) and finite-length (3-D) flaws in unclad RPV material. Specific areas of assistance will include (a) providing guidance in refining the test-specimen design for 3-D flaws; (b) providing recommendations for the test matrices; (c) performing a technical review of appropriate test specifications; (d) assisting in the interpretation of test data to identify significant biaxial loading effects; and (e) providing assistance in the production of reports on the shallow-flaw testing program.

Task 3: Provide consultation and guidance in the execution and interpretation of the shallow-flaw fracture toughness tests of full-thickness clad beams cut from surplus reactor pressure vessels (RPVs). These tests are being performed for the HSST Program at the National Institute of Standards and Technology (NIST) under an Interagency Agreement. Specific areas of assistance include (a) reviewing test specifications; (b) interpreting test data, with emphasis on the effects of both metallurgical inhomogeneities and crack-depth-to-specimen-depth (a/W) ratio; and (c) providing assistance in the production of reports on the full-thickness clad-beam testing program.

Task 7: Provide consultation and guidance in integrating and assessing test data and analysis results from other HSST Tasks for purposes of developing RPV fracture assessment methodologies to be used by the NRC. Specific areas of assistance include (a) assessing shallow-flaw and biaxial constraint effects on both the applied crack driving force and the material fracture toughness; and (b) performing technical reviews of documents prepared in support of this Task. In addition, Professor Rolfe will provide feedback to the HSST program of information relating to fracture technology derived from his membership in the Pressure Vessel Research Council of the Welding Research Institute.

B. Basis for Consultant Selection

Professor Stanley T. Rolfe has been involved in a comprehensive experimental and analytical research program in fracture mechanics at the University of Kansas for 20 years. Prior to that time he was Division Chief of the Material Behavior Division at U.S. Steel's Applied Research Laboratory in Monroeville, Pennsylvania. He has an extensive research background and considerable practical experience in the application of fracture mechanics to various fracture and fatigue problems. His research for the Pressure Vessel Research Committee and the American Iron and Steel Institute has focused on elastic-plastic fracture mechanics test development as well as fatigue and fracture control in steel structures. He has published extensively in the fields of fracture control, test development, correlations, CTOD test development, and applications of fracture mechanics. He has a textbook on

"Fracture and Fatigue Control in Structures," co-authored by John Barsom of U.S. Steel. He has consulted widely on structural failures and is recognized as a leading expert in the field of fatigue and fracture control.. Dr. Rolfe provided consultation support to the HSST shallow-flaw fracture toughness testing program in FY 1991, 1992, 1993, and 1994. His expert advice was instrumental in guiding a number of key program decisions, and his review of results was particularly valuable.

9.1.2 FY 1996

Task Number	H.2	H.3	H.4	H.6	H.7	Totals
Subcontractor/Consultant	K$	K$	K$	K$	K$	K$
Subcontractors						
University of Maryland	15	35				50
University of Illinois		3*	20			23
National Institute of Standards and Technology		6*				6
Battelle Memorial Institute, Columbus Division				16*		16
Naval Surface Warfare Center				14*		14
Consultants						
Professor S. T. Rolfe	5	10			5	20
FY 1996 Totals	20	54	20	30	5	129

Items marked thus * are carry over subcontract obligations from FY 1995.

9.1.2.1 University of Maryland

A. Subcontract Work Package Scope and Objectives

Task 2 To assist ORNL in an evaluation of the effects of biaxial loading and flaw depth on fracture toughness, metallurgical examinations will be performed on selected fracture surfaces from the flaw depth verification test matrix. The location of initiation site(s) relative to the pre-cracked flaw tip will be determined. The fracture surfaces will also be sectioned at 90° to the flaw plane in the area of the primary initiation site. The cross-sectional surface developed in this manner will be polished and etched, measurements of the crack tip radius will be made, and a determination of the extent of the plastic zone size will be performed. This information will be used by ORNL for evaluations of the constraint methodologies being considered, with particular attention being directed to the strain-based dual-parameter fracture model. The results of these metallurgical examinations will be published in a letter report.

Task 3: Metallurgical examinations will be performed on fracture surfaces from the matrix of verification tests conducted with intermediate-scale clad cruciform specimens containing shallow surface flaws. The extent of crack growth during the fatiguing process and the geometry of the through-clad fatigued surface flaw will be measured. Also, the amount of pre-cleavage ductile tearing and the location of the initiation site(s) relative to the initial fatigued flaw tip will be recorded. For selected specimens, the fracture surface will be sectioned in a plane normal to the crack front in the area of the primary initiation site. Measurements of the crack-tip radius and the extent of the plastic zone will be made for use in evaluating dual-parameter fracture correlation methodologies. Results of these metallurgical studies will be published in a letter report.

9.1.2.2 University of Illinois

A. Subcontract Work Package Scope and Objectives

Task 4: The preliminary fracture-mode-conversion model will undergo validation procedures and modifications will be made to the model based on the validation study. As part of the model modifications, an investigation will be carried out to determine the difference in the stress field ahead of a growing crack using the Gurson model and crack-tip-opening angle failure criteria. Also, the affect of pre-cleavage ductile tearing on the D-A toughness scaling model and Weibull stress calculations will be investigated. The subcontractor will provide consultation and guidance in developing empirical relationships that will be generated from the final analysis results and implemented in deterministic and probabilistic fracture codes, and assistance in the production of reports.

9.1.2.3 Professor S. T. Rolfe

A. Subcontract Work Package Scope and Objectives

Task 2: Provide consultation and guidance to assist in refinement of the testing program for biaxial loading and flaw depth effects [constant-depth (2-D) flaws]. Specific areas of assistance will include (a) providing recommendations for the test matrices to be executed; (b) performing a technical review of test specification; (c) providing assistance in the interpretation of test data to assess biaxial loading and flaw depth effects; and (d) providing assistance in the production of reports on the biaxial loading testing program.

Task 3: Consultation and guidance will be provided to the cladding effects testing program utilizing intermediate-scale clad cruciform specimens with shallow surface flaws. Specific areas of assistance will include (a) providing a technical review of test specifications; (b) providing assistance in the interpretation of test data to assess cladding effects on shallow flaw behavior; and (c) providing assistance in the completion of reports on cladding effects on fracture toughness under biaxial loading.

Task 7: Provide consultation and guidance in integrating and assessing test data and analysis results from other HSST Tasks for purposes of developing RPV fracture assessment methodologies to be used by the NRC. Specific areas of assistance include (a) assessing shallow-flaw and biaxial constraint effects on both the applied crack driving force and the material fracture toughness; and (b) performing technical reviews of documents prepared in support of this Task. In addition, Professor Rolfe will provide feedback to the HSST Program of information relating to fracture technology derived from his membership in the Pressure Vessel Research Committee of the Welding Research Council.

9.1.3 FY 1997

Task Number	**H.2**	**H.3**	**H.4**	**H.6**	**H.7**	**Totals**
Subcontractor/Consultant	**K$**	**K$**	**K$**	**K$**	**K$**	**K$**
Subcontractors						
University of Maryland	15	15				30
University of Illinois			15			15
Consultants						
Professor S. T. Rolfe	5				5	10
FY 1997 Totals	20	15	15		5	55

9.1.3.1 University of Maryland

A. Subcontract Work Package Scope and Objectives

Task 2: To assist ORNL in an evaluation of the transferability from laboratory- to large-scale structural behavior of the constraint methodologies being assessed, metallurgical examinations will be performed on selected specimen fracture surfaces from the unclad, 2-D flaw beam test matrix. Non-destructive and destructive examinations will be performed to measure initiation site location, crack tip radius, and extent of the plastic zone size. The information developed will be used by ORNL to assess the performance of the constraint methodologies application to RPV thickness materials. The results of these metallurgical examinations will be published in a letter report.

Task 3: Metallurgical examinations will be performed on fracture surfaces from the matrix of tests conducted for large-scale clad cruciform specimens containing shallow surface flaws. Measurements will be made to determine fatigue crack growth, initial fatigue-flaw geometry, initiation site location(s), crack tip radius, and extent of plastic zone size. The metallurgical data will be used to assess the performance of dual-parameter constraint methodologies applicable to RPV materials in the transition temperature region. Results of these metallurgical studies will be published in a letter report.

9.1.3.2 University of Illinois

A. Subcontract Work Package Scope and Objectives

Task 4: Provide consultation and guidance in integrating and assessing analysis results for modifications to the predictive engineering methodology based on validation test results. Specific areas of assistance include (a) reviewing posttest analyses to determine the predictive capabilities of the methodology, (b) assessing modifications to the methodology, and (c) providing assistance in the production of reports.

9.1.3.3 Professor S. T. Rolfe

A. Subcontract Work Package Scope and Objectives

Task 2: Provide consultation and guidance to assist in definition of the large-scale cruciform beam testing program for constant-depth (2-D) flaws in unclad RPV material. Specific areas of assistance will include (a) review of and recommendations for the test matrices to be executed, (b) performing a technical review of test specification; (c) providing assistance in the interpretation of test data to assess biaxial loading and flaw depth effects; and (d) providing assistance an assessment of constraint methodology transferability and in production of reports for the biaxial test program.

Task 3: Consultation and guidance will be provided to the cladding effects testing program utilizing large-scale clad cruciform specimens with shallow surface flaws. Specific areas of assistance will include (a) providing a technical review of test specifications; (b) providing assistance in the interpretation of test data to assess cladding effects on shallow flaw behavior; and (c) providing assistance in the completion of reports describing the influence of cladding effects in RPV integrity assessments.

Task 7: Provide consultation and guidance in integrating and assessing test data and analysis results from other HSST Tasks for purposes of developing RPV fracture assessment methodologies to be used by the NRC. Specific areas of assistance include (a) assessing shallow-flaw and biaxial constraint effects on both the applied crack driving force and the material fracture toughness; and (b) performing technical reviews of documents prepared in support of this Task. In addition, Professor Rolfe will provide feedback to the HSST Program of information relating to fracture technology derived from his membership in the Pressure Vessel Research Committee of the Welding Research Council.

9.1.4 FY 1998

Task Number	H.1	H.3	H.4	H.6	H.7	Totals
Subcontractor/Consultant	K$	K$	K$	K$	K$	K$
Subcontractors						
Westinghouse Electric Corporation	62*					62*
University of Maryland					5	5
University of Illinois					5	5
Consultants						
Professor S. T. Rolfe					5	5
FY 1998 Totals	62*				15	77

Items marked thus * are carry over subcontract obligations from FY 1994.

9.1.4.1 Westinghouse Electric Corporation

A. Subcontract Work Package Scope and Objectives

Task 1: The purpose of this work was to further determine crack growth rates in RPV base metals, weldments, and heat-affected zones. Data were developed over temperature ranges with fluid environments representative of light-water reactor operating conditions. The effects of sulfur content and other compositional factors on crack-growth rates were determined in well controlled water environments. Data from the cyclic tests and stress-corrosion-cracking tests were correlated. Topical reports and semi-annual progress reports were prepared.

Work on this subcontract was completed in 1986. At completion of work on the subcontract, $62K of the assigned funding remained unspent. In 1992, the unspent funding was added to the HSST Program funding, pending completion of a DCAA audit of the Westinghouse subcontract. Upon successful completion of the DCAA audit, the unspent balance must be returned to NRC. The $62K obligation in FY 1998 is based upon the assumption that the DCAA audit will be completed on or before that time.

9.1.4.2 University of Maryland

A. Consulting Work Package Scope and Objectives

Task 7: Additional metallurgical examinations will be performed on fracture surfaces from the matrix of tests conducted for clad cruciform specimens containing shallow surface flaws. Measurements will be made to determine fatigue crack growth, initial fatigue-flaw-geometry, initiation site location(s), crack tip radius, and extent of plastic zone size. The metallurgical data will be used to assess the performance of dual-parameter constraint methodologies applicable to RPV materials in the transition temperature region. Results of these metallurgical studies will contribute to final program reports.

9.1.4.3 University of Illinois

A. Consulting Work Package Scope and Objectives

Task 7: Provide consultation and guidance in integrating and assessing analysis results for constraint effects and the predictive mode conversion methodology based on validation test results. Specific areas of assistance include (a) reviewing posttest analyses, (b) assessing modifications to the methodologies, and (c) providing assistance in the production of reports.

9.1.4.4 Professor S. T. Rolfe

A. Consulting Work Package Scope and Objectives

Task 7: Provide consultation and guidance in integrating and assessing test data and analysis results from other HSST Tasks for purposes of developing RPV fracture assessment methodologies to be used by the NRC. Specific areas of assistance include (a) assessing shallow-flaw and biaxial constraint effects on both the applied crack driving force and the material fracture toughness; and (b) performing technical reviews of documents prepared in support of this Task. In addition, Professor Rolfe will provide feedback to the HSST Program of information relating to fracture technology derived from his membership in the Pressure Vessel Research Committee of the Welding Research Council.

9.1.5 FY 1999 (10/1/98-12/31/98)

No subcontract or consultant support is planned for FY 1999.

9.2 Materials and Services

9.2.1 FY 1995

Materials and services (M&S) expenditures proposed for the FY 1995 performance period are as follows.

Task	Material or Service	Cost (K$)
A.	Subcontract Services for Specific Tasks	
H.1	Express mail services	1
H.2	Purchase of a 9 gigabyte external hard drive for the IBM RISC 6000 work station. This equipment is required to accommodate the large volume of data generated in 3-D nonlinear analyses of crack-tip stress fields.	5
H.2	Heat treatment of the HSST plate 14 A 533 B material to simulate the properties of irradiated reactor vessel material	16
H.2	Lease of an IBM RISC 6000 Model 560 workstation	18 (50 percent of cost)
H.2	Maintenance support for the IBM RISC 6000 Model 560 workstation	3 (50 percent of cost)
H.2	Lease of the ABAQUS computer program	3 (50 percent of cost)
H.2	Fabrication of 19 cruciform test specimens with constant depth flaws from the heat treated Plate 14 material	56
H.2	Characterization tests of the heat treated material	3
H.2	Instron test machine capacity upgrade and calibration as described in Section 10	22 (50 percent of cost)
H.2	Testing of plane-strain CTOD specimens	15
H.2	Test specimen instrumentation procurement and services	15
H2	Cut up of plate 14 to form blanks for the cruciform specimens	10
H2	Miscellaneous material shipping costs and shop supplies	3
H.3	Lease of an IBM RISC 6000 Model 560 workstation	18 (50 percent of cost)
H.3	Maintenance support for the IBM RISC 600 Model 560 workstation	3 (50 percent of cost)
H.3	Lease of the ABAQUS computer program	3 (50 percent of cost)

H.3	Characterization tests of the SNUPPS shell segment reactor vessel material	10
H.3	Instron test machine capacity upgrade and calibration as described in section 10	21 (50 percent of cost)
H.3	Test specimen instrumentation procurement and services	2
H.3	Upgrade of the biaxial test fixture capacity and size to accommodate large-scale test specimens.	36
H3	Cut up of SNUPPS shell material to form blanks for the clad cruciform specimens	5
H3	Fabrication and shipping of full-scale shallow flaw beam specimens and shipping of the specimens to NIST	7
H3	Miscellaneous material shipping costs and shop supplies	3
H.4	Fabrication of specimens for J-R testing of the SNUPPS weld material	2
B. ORNL Services for Multiple Tasks		
	Instrumentation and Control Group services	5
	NRC Programs Office services	56
	Computer Programming services	2
	Reports Group services	49
	Procurement Services	7
	Y-12 Plant services	34
	K-25 Plant services	14
Total materials and services charges in FY 1995		447

9.2.2 FY 1996

Materials and services (M&S) expenditures proposed for the FY 1995 performance period are as follows.

Task	Material or Service	Cost (K$)
A.	Subcontract Services for Specific Tasks	
H.1	Express mail services	1
H.1	Purchase of paper reprints from Professional Societies	1
H.1	Procurement of a shell segment from the Reactor Pressure Vessel Research Users' Facility (PVRUF) RPV	98

H.1	Procurement of additional services during the cut-up of the PVRUF	7
H.1	Removal of intermediate vessel V-10 from the K-25 power house and transport of the vessel to the HSST program material storage yard at the Y-12 site	2
H.2	Maintenance support for the IBM RISC 6000 Model 560 workstation	4 (50 percent of cost)
H.2	Lease of the ABAQUS computer program	4 (50 percent of cost)
H.2	Fabrication of 5 cruciform test specimens with constant depth flaws from the heat treated Plate 14 material. This is the balance of a batch of 24 specimens on which fabrication was started in FY1995.	13
H.2	Fabrication of eight intermediate-size cruciform test specimens with constant depth flaws from the heat treated material. These specimens will have flaw aspect ratios (a/w) of .05 and .15	45
H.2	Fabrication of four large cruciform test specimens with constant depth flaws from the heat treated material	60
H.2	Fabrication of a lifting fixture for the large-scale cruciform specimen	10
H.2	Large-range Shepic clip gauges	15
H.2	Characterization tests of the heat treated material	10
H.2	Testing of plane-strain CTOD speicmens	12
H.2	Test specimen instrumentation procurement and services	20
H.3	Lease of the ABAQUS computer program	4 (50 percent of cost)
H.3	Maintenance support for the IBM RISC 600 Model 560 workstation	4 (50 percent of cost)
H.3	Fabrication of 24 intermediate-size clad cruciform test specimens with finite length surfact flaws from the SNUPPS reactor pressure vessel shell segments	130
H.3	Fabrication of one large-scale clad-cruciform specimen with a finite-length surface flaw from the SNUPPS reactor pressure vessel shell segments	30
H.3	Test specimen instrumentation	8
H.4	Fabrication of specimens for J-R testing of SNUPPS weld and plate material	10
H.6	Open purchase order from FY 1994 for chemical analyses services from ABB Combustion Engineering in support of development of a clad finite-length-flaw cruciform test specimen with simulated prototypical irradiated stainless steel cladding properties	5

B. ORNL Services for Multiple Tasks

Instrumentation and Control Group services	9
NRC Programs Office services	50
Computer Programming services	5
Reports Group services	38
K-25 Plant services	8
Y-12 Plant services	24
Total materials and services charges in FY 1996	627

9.2.3 FY 1997

Materials and services (M&S) expenditures proposed for FY 1997 are as follows.

Task	Material or Service	Cost (K$)
A.	Subcontract Services for Specific Tasks	
H.1	Express mail services	1
H.1	Purchase of paper reprints from Professional Societies	1
H.2	Maintenance support for the IBM RISC 6000 Model 560 workstation	5 (50 percent of cost)
H.2	Lease of the ABAQUS computer program	5 (50 percent of cost)
H.2	Fabrication of two large-scale cruciform test specimens with constant depth flaws from the heat treated Plate 14 material.	57
H.2	Testing of plane-strain CTOD specimens	20
H.2	Test specimen instrumentation procurement and services	20
H.3	Maintenance support for the IBM RISC 600 Model 560 workstation	5 (50 percent of cost)
H.3	Lease of the ABAQUS computer program	5 (50 percent of cost)
H.3	Test specimen instrumentation and services	5
H.3	Fabrication of three large-scale clad cruciform test specimens with finite length surface flaws from the SNUPPS reactor pressure vessel shell segments.	71

B. ORNL Services for Multiple Tasks

	NRC Programs Office services	50
	Computer Programming services	6
	Reports Group services	64
	Y-12 Plant services	25
Total materials and services charges in FY 1997		340

9.2.4 FY 1998

Materials and services (M&S) expenditures proposed for FY 1998 are as follows.

Task	Material or Service	Cost (K$)
A.	Subcontract Services for Specific Tasks	
H.1	Express mail services	1
H.1	Purchase of paper reprints from Professional Societies	1
H.7	Maintenance support for the IBM RISC 6000 Model 560 workstation	10
H.7	Lease of the ABAQUS computer program	10
B.	ORNL Services for Multiple Tasks	
	NRC Programs Office services	50
	Reports Group services	64
Total materials and services charges in FY 1998		136

9.2.5 FY 1999 (10/1/98-12/31/98)

Materials and services (M&S) expenditures proposed for the first three months of FY 1999 are as follows.

Task	Material or Service	Cost (K$)
A.	Subcontract Services for Specific Tasks	

There are no subcontract services planned for this period.

B.	ORNL Services for Multiple Tasks	
	NRC Programs Office services	12
	Reports Group services	46
Total materials and services charges in FY 1999		58

10. SPECIAL FACILITIES, IF REQUIRED:

The full-scale uniaxial shallow-flaw fracture toughness tests will require the use of the existing 27MN (12 M lb) test machine at the National Institute of Standards and Testing, Gaithersburg, Maryland.

The dynamic fracture toughness tests will require a special purpose dynamic testing machines that exists at the Carderock Division of the Naval Surface Warfare Center.

The large-scale biaxial tests will require that the biaxial test fixture and the Instron Model 1336 test machine at ORNL be upgraded to increase the load capacity to 700 kips (the load capacity is currently 550 kips). The Instron company has confirmed that the test machine capacity can be increased to 700 kips by changing the control system and recalibrating the machine. ORNL studies have confirmed that the test-fixture capacity can be increased to 700 kips by manufacturing a new base plate and reusing the balance of the existing biaxial-fixture hardware. The new base plate will also permit the test specimen moment arm length to be increased.

11. CONFLICT-OF-INTEREST INFORMATION:

There are no know relationships between this organization or its employees or subcontractors with industries regulated by the NRC and suppliers thereof that might give rise to an apparent or actual conflict of interest regarding work described in this proposal.

12. CLASSIFICATION OR SENSITIVITY, IF APPLICABLE (e.g., safeguards, proprietary, other):

The worked defined in the SOW is not classified or sensitive. Reports generated in response to this SOW will not contain any proprietary (including unit-specific Nuclear Plant Reliability Data System data), confidential, or copyrighted material without written permission from the institutions and organizations to which the information may belong.

13. ADDENDUM:

A) INTERPRETATIONS OF STATEMENT OF WORK

Task 5

Subtask 5.2

Pressure-temperature time histories for the PTS transients required as input to Subtask 5.2 b (see paragraph 3.3.5.2.b) will be provided by NRC.

In order to meet the milestone for FY 97, the thermal-hydraulic data must be received as follows:

H.B Robinson	**9/30/96**
Plant no. 2	**4/30/97**

NRC FORM 189 (Continued)
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U.S. NUCLEAR REGULATORY COMMISSION

DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK

JOB CODE B0119

DATE JULY 19, 1996

PROJECT TITLE: Heavy Section Steel Technology

13. (B) Cost Information

Estimated Cost Schedule ($K)

	Prior Years	1995	1996	1997	1998	1999	Total
Task 1	346	323	508	386	432	139	2134
Task 2	900	734	679	451			2764
Task 3	550	662	736	444			2392
Task 4	108	213	213	174			708
Task 5	242	163	207	216	15		843
Task 6	482	408	94				984
Task 7	231	300	302	271	1320	743	3167
Task 8							
Task 9							
Task 10							
Task 11							
Task 12							
Task 13							
Task 14							
Task 15							
Task 16							
Task 17							
Task 18							
Task 19							
Task 20							
Previously Completed Tasks	74151						74151
Subtotal	77010	2803	2739	1942	1767	882	87143
DOE Added Factor	282	121	118	84	76	38	719
Total (Costs)	77292	2924	2857	2026	1843	920	87862
Carryover from Prior Year		(1905)	(1626)	(709)	(483)	(440)	0
Carryover to Next Year	1905	1626	709	483	440	0	0
Total (Funding)	79197	2645	1940	1800	1800	480	87862

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13. (C) Schedule Information (Continued)

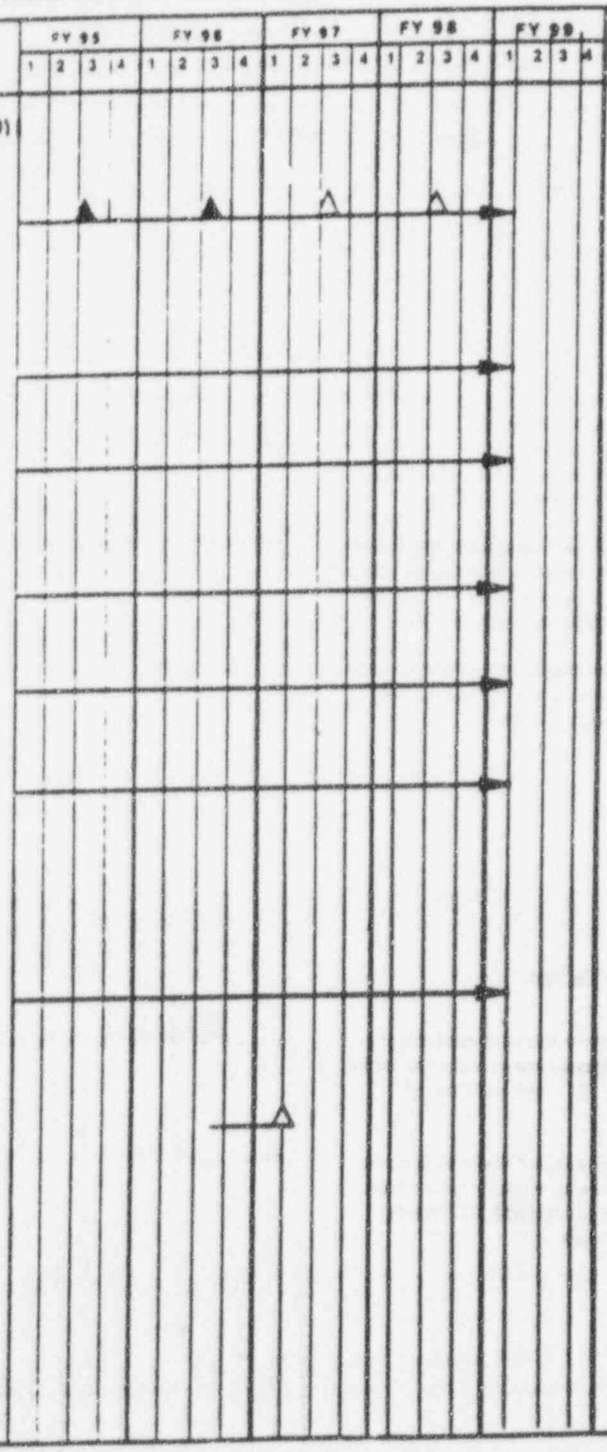
Subtask/Milestone Schedule

Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
H.1 PROGRAM MANAGEMENT																				
H.1.1 Monitoring and Control																				
A. Update the HSST Program cost estimating and performance tracking software as required to reflect any customer-directed changes in the program work breakdown structure.																				
B. Monitor progress against objectives for each of the program tasks using earned value system with cost/schedule variance analysis.																				
C. Implement corrective actions for any performance problems identified and monitor their effectiveness.																				
D. Issue monthly progress reports giving a summary of technical progress, cost/schedule performance and the program financial status and identifying any problems.																				
H.1.2 Program Planning																				
A. Plan a research program responsive to the NRC HSST Program Assumptions and secure the resources necessary for its implementation.																				
B. Prepare and issue HSST Program 189.																				
C. Prepare and implement corrective action plans as necessary to overcome any problems encountered in execution of the program plan.																				

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

SUBTASK/MILESTONE



H.1 PROGRAM MANAGEMENT (CONT'D)

H.1.3 Subcontract Management

A. Identify needs for subcontracts to secure facilities and/or services necessary for the efficient execution of the program work scope.

B. Negotiate for program subcontract support with vendors and consultants.

C. Define the work scope and deliverables for subcontracts, prepare the procurement packages and place the subcontracts.

D. Integrate subcontractor activities with those of the ORNL research teams.

E. Monitor subcontractor performance; implement corrective actions if necessary.

F. Review subcontractor research results and prepare them for publication.

H.1.4 Procurement

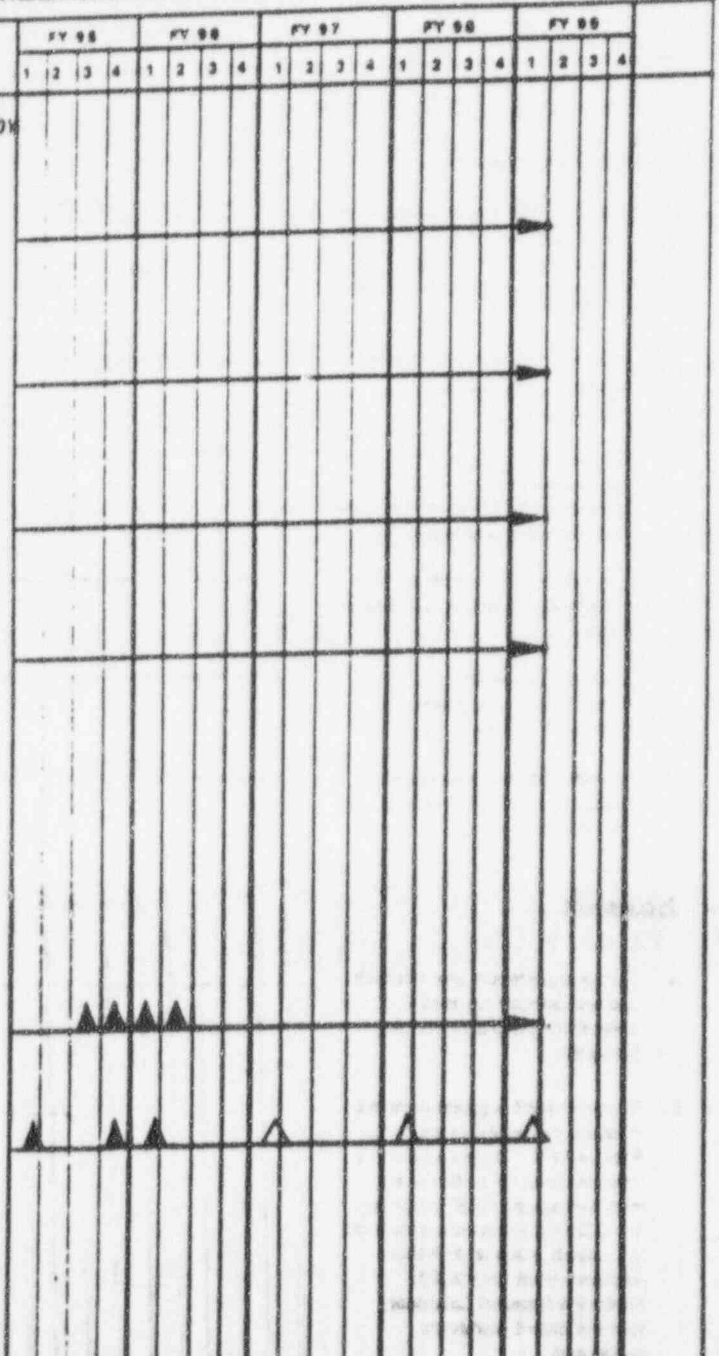
A. Locate and procure any materials and components required to support the program research activities.

B. Procure a shell segment from the Pressure Vessel Research Users' Facility RPV. The material to be procured shall be sufficient to meet anticipated HSST program needs for test specimen fabrication and include material on which personnel from the Pacific Northwest National Laboratory have performed ultrasonic inspections.

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

SUBTASK/MILESTONE



H.1 PROGRAM MANAGEMENT (CONT'D)

H.1.5 Quality Control

A. Implement and maintain a quality control program and monitor to assure the QA program requirements are met.

B. Review and approve all program reports, papers and presentations and ensure program quality control requirements are met prior to their publication.

C. Conduct readiness reviews prior to the release of any new test facility or facility modification for the conduct of program tests.

D. Conduct periodic reviews of the ongoing work in each of the program tasks.

H.1.6 Project Briefings

A. **Prepare and deliver briefings on program activities as directed by the NRC Project Manager.**

B. **Prepare and deliver interpretive papers on program research as directed by the NRC Project Manager.**

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone

H.1 PROGRAM MANAGEMENT (CONT'D)

H.1.7 Program Reviews

A. Coordinate NRC and ORNL Program review activities

H.1.8 Information Exchanges

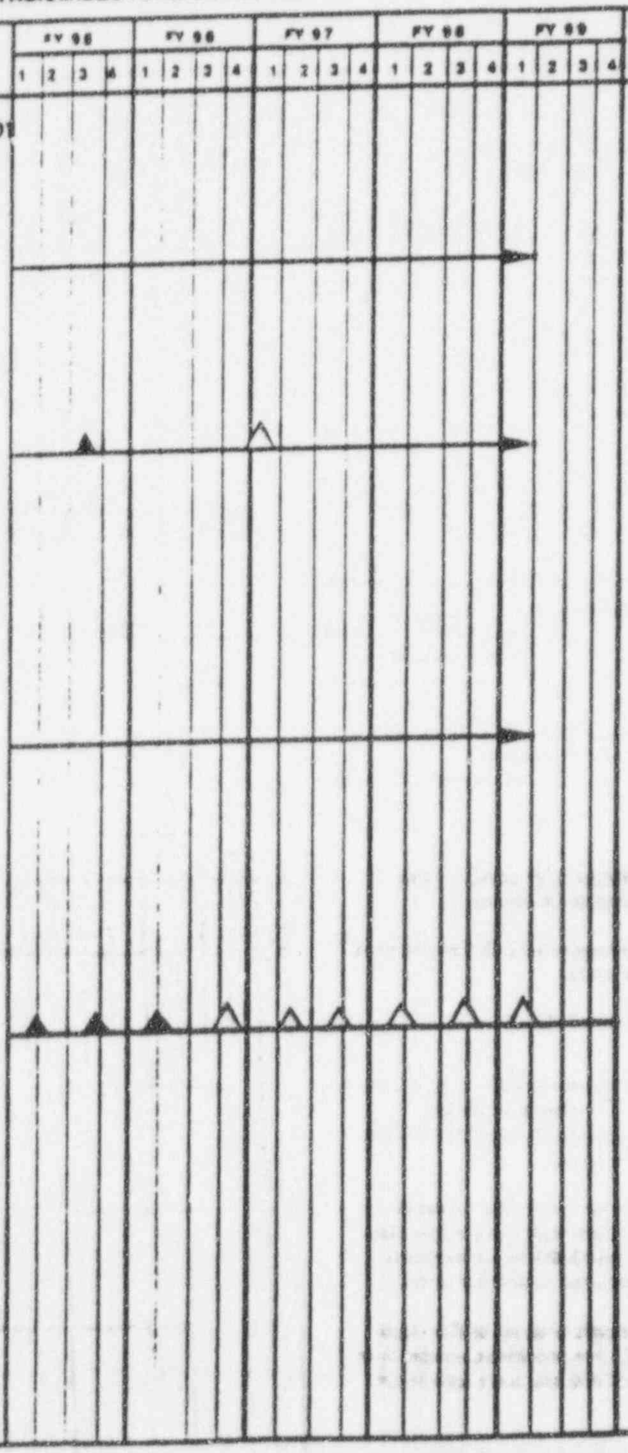
A. Coordinate information exchanges and technology transfer with national and international organizations as directed by the NRC Project Manager.

H.1.9 Program Coordination

A. Maintain close liaison with the HSSI program to assure the HSST/HSSI program activities are well coordinated and integrated.

H.1.10 Reporting

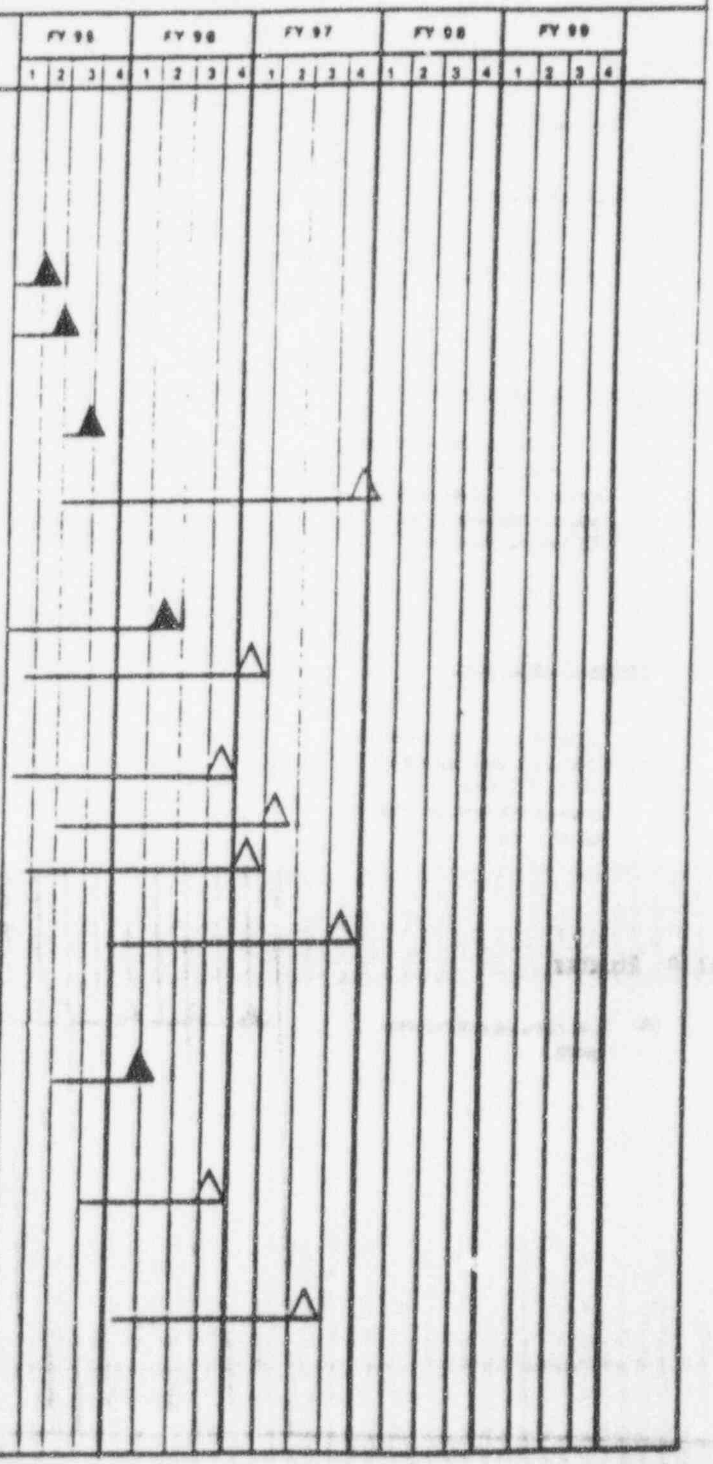
A. Issue semi-annual progress reports.



13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone



H.2 CONSTRAINT EFFECTS ANALYTICAL AND VALIDATION DEVELOPMENT

H.2.1 Biaxial Loading Effects Validation Testing

A. Develop heat-treat specification.

B. Heat-treat segment of Plate 14

C. Characterize Plate 14 in heat treated condition.
1. For loading effects validation testing and analysis
2. For all 2-D flaw cruciform tests.

D. Fabricate intermediate-size cruciform specimens.
1. Loading effects validation Phase I and Phase II).
2. Flaw depth validation

E. Complete testing of intermediate-size cruciform specimens.
1. Loading effects validation Phase I and Phase II).
2. Flaw depth validation

F. Fabricate large-scale 2-D flaw cruciform specimens.

G. Test large-scale 2-D flaw cruciform specimens.

H.2.1.2 Analysis Support

A. Complete analyses of Phase I load-ratio cruciform specimens, interpretation of test data and issue letter report.

B. Analyze full matrix of load-ratio cruciform tests using refined flaw-tip model, determine toughness values, and issue letter report.

C. Complete analyses of flaw-depth cruciform specimens, interpretation of test data and issue letter report.

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone

H.2 CONSTRAINT EFFECTS ANALYTICAL AND VALIDATION DEVELOPMENT (CONT'D)

D. Pre-test analysis of large-scale tests.

E. Complete analyses of large-scale cruciform specimens, interpretation of test data, and issue letter report.

H.2.2 <u>Constraint Effects Correlation</u>

A. Implement near-tip tearing model and validate operation.

B. Perform near-tip analyses of tearing model.

C. Apply ductility-based constraint criteria to data.

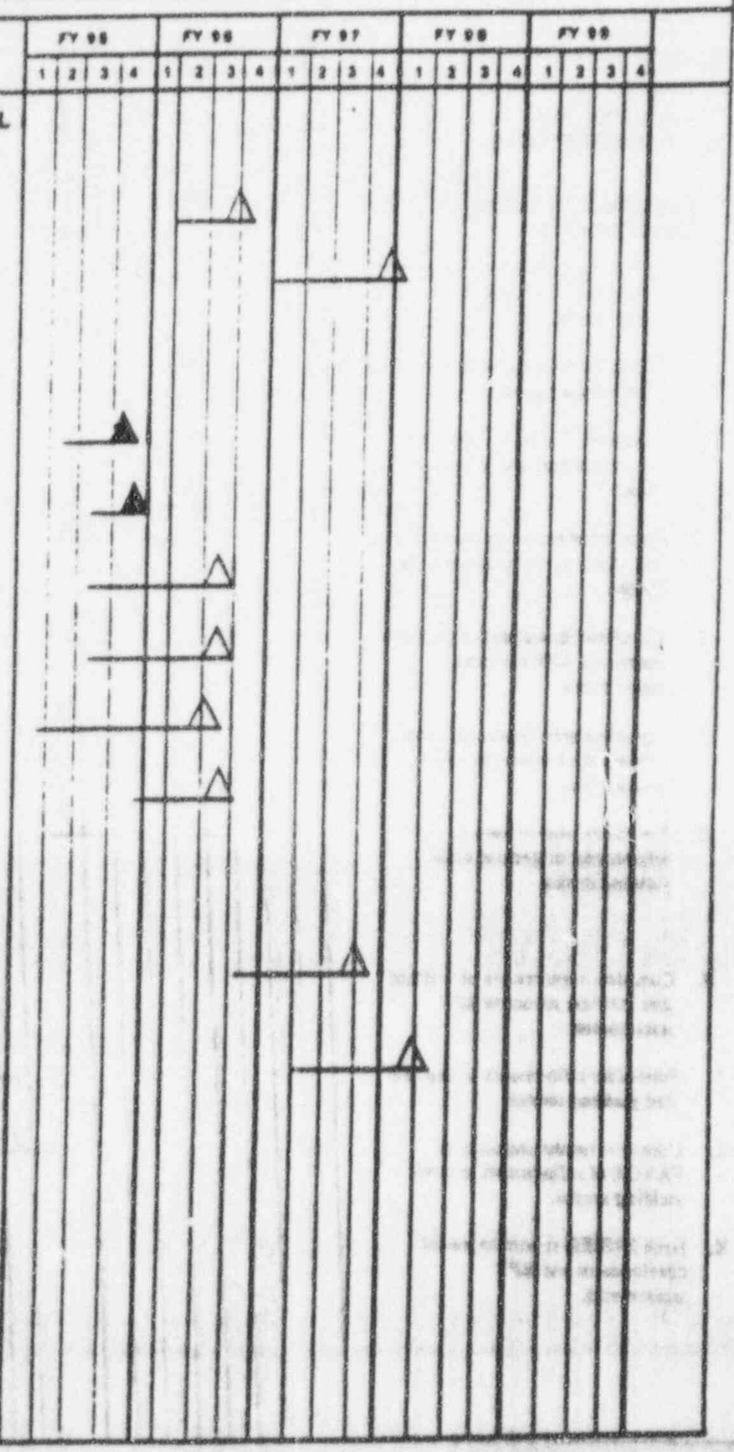
D. Apply stress-strain-based constraint criteria to data.

E. Complete fractographic analysis of selected fracture surfaces.

F. Complete constraint interpretations of available test data and publish results in NUREG.

G. Apply stress-strain-based and ductility-based constraint methodologies to new data and issue letter report.

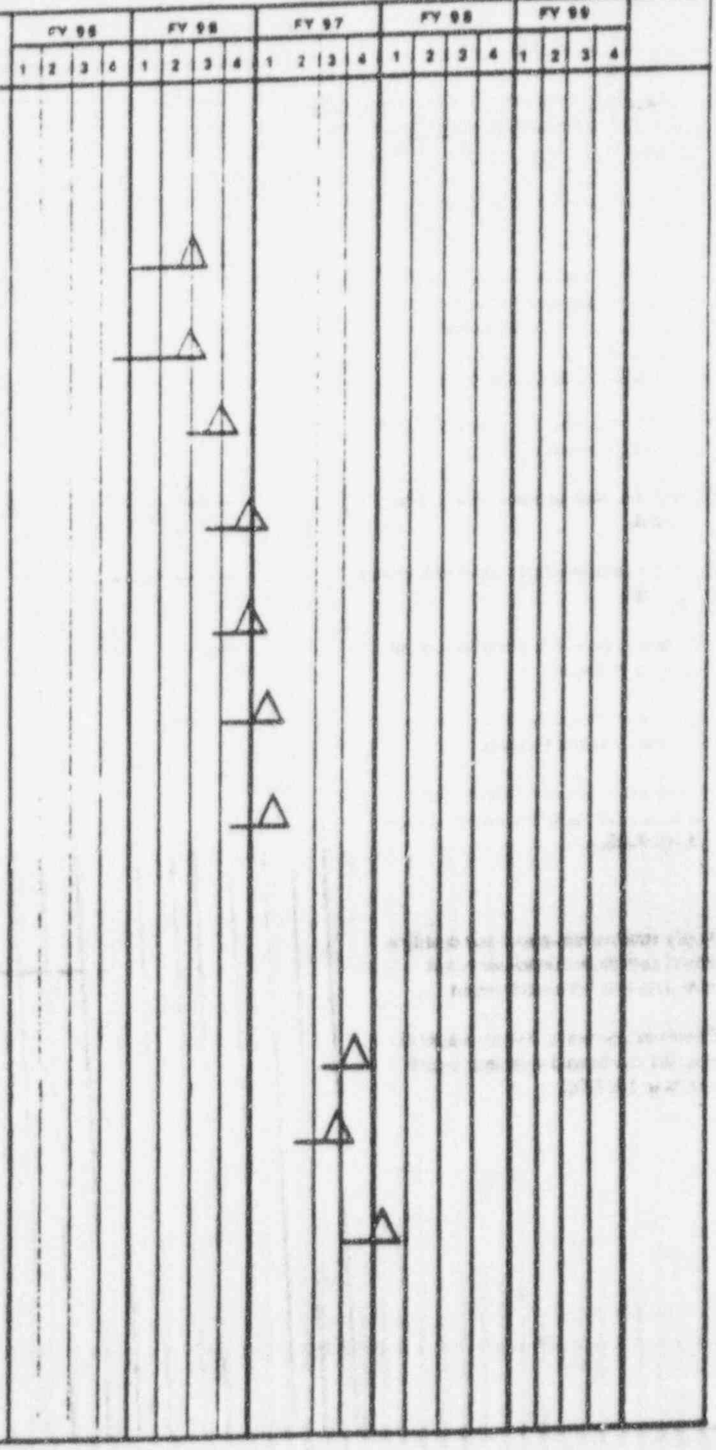
H. Complete constraint interpretations of uniaxial and biaxial data and publish results in NUREG.



13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

SUBTASK/ MILESTONE



H.3 EVALUATION OF CLADDING EFFECTS

H.3.1 <u>Quasi-static Clad-Yielding Model Development</u>

A. Complete formulation of generic model incorporating clad-yield stress effects.

B. Complete analysis matrix defining clad-yielding model.

C. Complete validation of clad-yielding model using available test data.

D. Issue letter report on development and validation of clad-yielding model.

E. Complete formulation of analysis matrix for RPV integrity assessments.

F. Complete applications of generic clad-yielding model to RPV assessments.

G. Formulate and implement refinements of generic clad-yielding model.

H. Complete applications of updated clad yielding model to RPV assessments.

I. Formulate refinements of updated clad yielding model.

J. Complete implementation in FAVOR of refinements to clad-yielding model.

K. Issue NUREG report on model development and RPV assessments.

NRC FORM 189 (Continued)
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U.S. NUCLEAR REGULATORY COMMISSION

DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK

JOB CODE: B0119

DATE: JULY 19, 1996

PROJECT TITLE: **Heavy Section Steel Technology**

13. (C) Schedule Information (Continued)

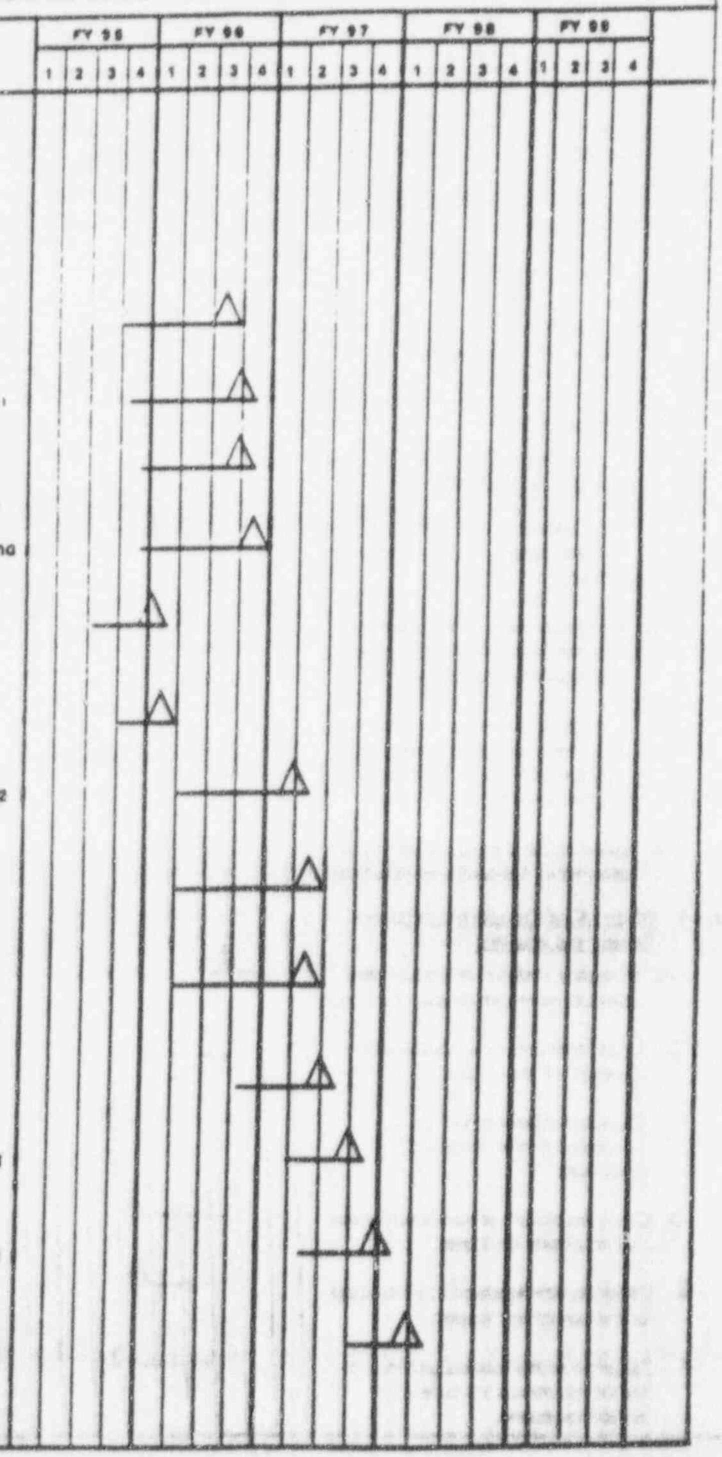
SUBTASK/MILESTONE SCHEDULE

SUBTASK/ MILESTONE	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
H.3 EVALUATION OF CLADDING EFFECTS (CONT'D.)																				
H.3.2 Cladding Method Development																				
A. Complete tensile, plane-strain-ductility, Charpy, and drop-weight tests for SNUPPS material.				▲																
B. Complete tests of sheet-type tensile specimens from cladding and HAZ.			▲																	
C. Issue letter report on material characterization.					△															
H.3.3 Uniaxial Full-Thickness Clad-Beam Testing and Analysis																				
A. Complete testing by NIST of three full-thickness clad beams provided by ORNL.			▲																	
B. Complete post-test finite element analyses of near-crack-tip region in full-thickness clad beams.				△																
C. Complete evaluation of the influence of material inhomogeneities and cladding process on fracture toughness.				△																
D. Issue NUREG report on testing and analysis of full-thickness clad beams.				△																
H.3.4 Biaxial Clad Cruciform Specimen Testing and Analysis																				
A. Complete analyses to predict non-initiating envelope of finite flaw sizes.		▲																		
B. Issue letter report on non-initiating envelope of flaw sizes.			△																	
C. Complete fabrication of six development clad cruciform specimens.						▲														
D. Complete testing of one development clad cruciform specimen.					▲															
E. Complete development of procedures for clad cruciform testing.					▲															
F. Complete computational analyses of clad cruciform test specimens for verification matrix.						△														

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

SUBTASK/ MILESTONE



H.3 EVALUATION OF CLADDING EFFECTS (CONT'D.)

H.3.4 Biaxial Clad Cruciform Specimen Testing and Analysis (CONT'D)

G. Complete fabrication of Group 1 (Phase 1) specimens for verification matrix.

H. Complete testing of Group 1 (Phase 1) specimens for verification matrix.

I. Complete post-test computational analyses of clad cruciform specimens.

J. Issue letter report describing testing and analysis of clad cruciform specimens.

K. Complete analyses to determine transferability of dual-parameter correlations.

L. Issue letter report on transferability of dual-parameter correlations.

M. Complete fabrication of remaining clad cruciform specimens for verification matrix (Phase 1 and 2).

N. Complete testing of remaining clad cruciform specimens for verification matrix.

O. Complete post-test computational analyses of remaining clad cruciform specimens.

P. Issue letter report on testing and analyses of clad cruciform specimens.

Q. Complete assessment of implications of biaxial toughness data base for fracture correlation models.

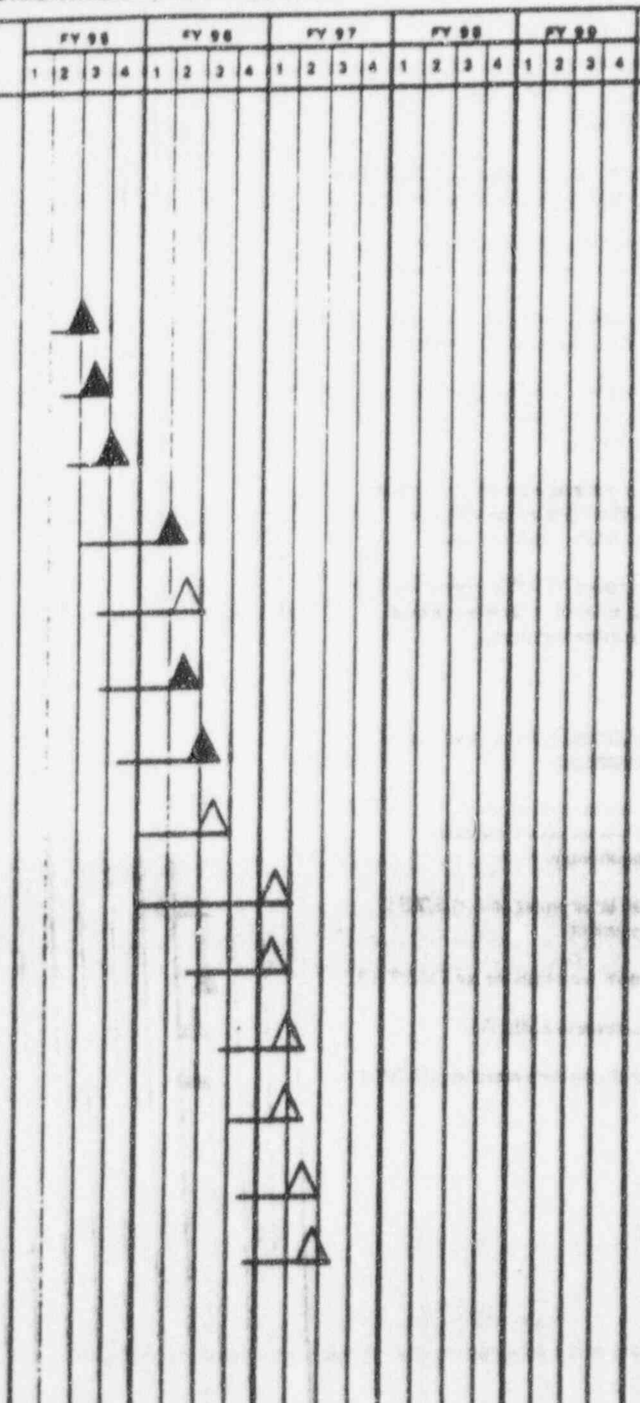
R. Complete assessment of implications of biaxial toughness data base for RPV integrity assessments.

S. Complete NUREG report on implications of biaxial toughness data base for fracture models and RPV assessments.

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

SUBTASK/ MILESTONE — FY 95 | FY 96 | FY 97 | FY 98 | FY 99 (quarters 1 2 3 4)



H.3 EVALUATION OF CLADDING EFFECTS (CONT'D.)

H.3.5 Large-Scale Clad Cruciform Specimen Testing and Analysis

A. Complete modifications of testing machine at ORNL.

B. Complete engineering drawings for test fixture and specimen.

C. Complete detail finite element analysis of clad cruciform model.

D. Complete procurement of hardware for test fixture.

E. Complete fabrication of dummy cruciform specimen.

F. Complete assembly and installation of test fixture.

G. Complete demonstration of test fixture fitness.

H. Issue letter report on progress of testing program.

I. Complete fabrication of clad cruciform specimen for first test.

J. Complete readiness review for first specimen test.

K. Complete first test of large clad cruciform specimen.

L. Complete post-test analysis of first large clad cruciform specimen.

M. Complete modifications of hardware and/or test procedures.

N. Issue letter report on progress of testing program.

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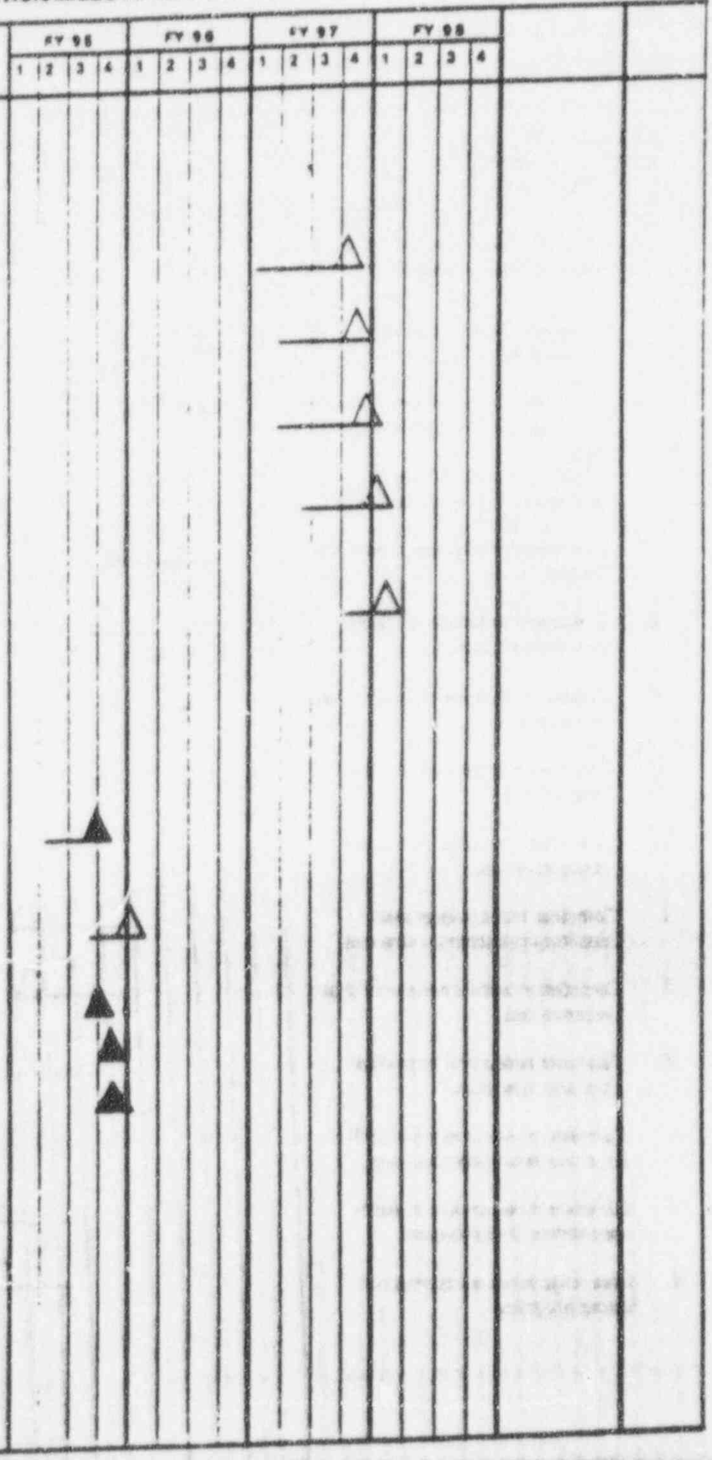
13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE



SUBTASK/MILESTONE	
H.3	**EVALUATION OF CLADDING EFFECTS (CONT'D.)**
H.3.5	Large-Scale Clad Cruciform Specimen Testing and Analysis (Continued)
O.	Complete fabrication of remaining large-scale clad cruciform specimens.
P.	Complete testing of remaining large-scale clad cruciform specimens.
Q.	Complete post-test analyses of remaining large-scale clad cruciform specimens.
R.	Complete assessments of fracture models using large-scale clad cruciform toughness data.
S.	Complete NUREG report on testing and analysis of large-scale clad cruciform specimens.
H.3.6	Validation Through International Participation
A.	Complete assessment of FALSIRE II for validation of [illegible] methodology.
B.	Issue letter report on FALSIRE II assessment.
C.	Prepare presentations for SMIRT-13.
D.	Participate in SMIRT-13.
E.	Issue foreign trip report on SMIRT-13.

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone	FY 95 1	FY 95 2	FY 95 3	FY 95 4	FY 96 1	FY 96 2	FY 96 3	FY 96 4	FY 97 1	FY 97 2	FY 97 3	FY 97 4	FY 98 1	FY 98 2	FY 98 3	FY 98 4	FY 99 1	FY 99 2	FY 99 3	FY 99 4
H.4 DUCTILE-TO-CLEAVAGE FRACTURE MODE CONVERSION																				
H.4.1 Metallurgical Investigation of Pre-Cleavage Ductile Tearing																				
A. Conduct fractographic examinations of the fracture surfaces for the materials of interest 1. characterize the extent of crack-tip blunting prior to crack growth. 2. identify and characterize the microstructural features associated with microvoid formation and growth. 3. identify and characterize the microstructural features responsible for mode conversion to cleavage, and 4. describe the relationship between the ductile crack morphology and the trigger points at mode conversion.	▲	▲																		
B. Issue letter report on the results from the metallurgical investigations outlined in H4.1.A.		▲																		
C. Perform J-R tests of the SNUPPS material for calibration of the fracture-mode-conversion model detailed in H4.2.		—	—	—	—	▲														
H.4.2 Fracture-Mode-Conversion Model																				
A. Issue letter report which focuses on methodologies that could contribute to the development of a fracture-mode-conversion model applicable to RPV steels in the transition temperature region, including a strategy for the development and validation of a fracture-mode-conversion model.		△																		
B. To complete the preliminary model development which considered the following items: 1. path dependence a. geometry changes resulting from crack tearing extension b. effects of work hardening of the crack-tip material prior to resharpening 2. void formation and coalescence models 3. crack advance model based upon the Dodds J-R approach 4. cleavage conversion criteria 5. mode conversion due to an increase in stress triaxiality 6. strain-rate sensitivity	—	—	—	—	—	△														

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99				BEYOND FY2000
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	
H.4.2 Fracture-mode-conversion Model Cont'd																					
C. Issue letter report on the preliminary fracture-mode-conversion model (detailed in H.4.2.B. and same as letter report H.4.3.B).					△																
D. Issue letter report on the generalized D-A constraint model. The report will focus on the modifications to the D-A toughness-scaling model for applications to biaxial loading conditions.					△																
H.4.3 Predictive Engineering Methodology																					
A. Develop methodology to include the preliminary fracture-mode-conversion model in deterministic and probabilistic fracture mechanics analyses. 1. Perform detailed parametric analyses with fracture-mode-conversion model for relevant range of: a. geometries b. transients c. loading conditions 2. Generate empirical relationships from the analyses results for implementation in deterministic and probabilistic fracture codes (i.e. FAVOR) 3. Modify fracture-mode-conversion model using data from parametric study					—	—	—	—	—	△											
B. Issue letter report on progress of the developed methodology to include the fracture-mode-conversion model in fracture mechanics analyses (same as H.4.2.C).					△																
C. Issue letter report on the preliminary methodology to include the fracture-mode-conversion model in fracture mechanics analyses.									△												

NRC FORM 189 (Continued) (10-93) NRCMD 11.7	U.S. NUCLEAR REGULATORY COMMISSION DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK	JOB CODE B0119 DATE JULY 19, 1996
PROJECT TITLE:	Heavy Section Steel Technology	

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

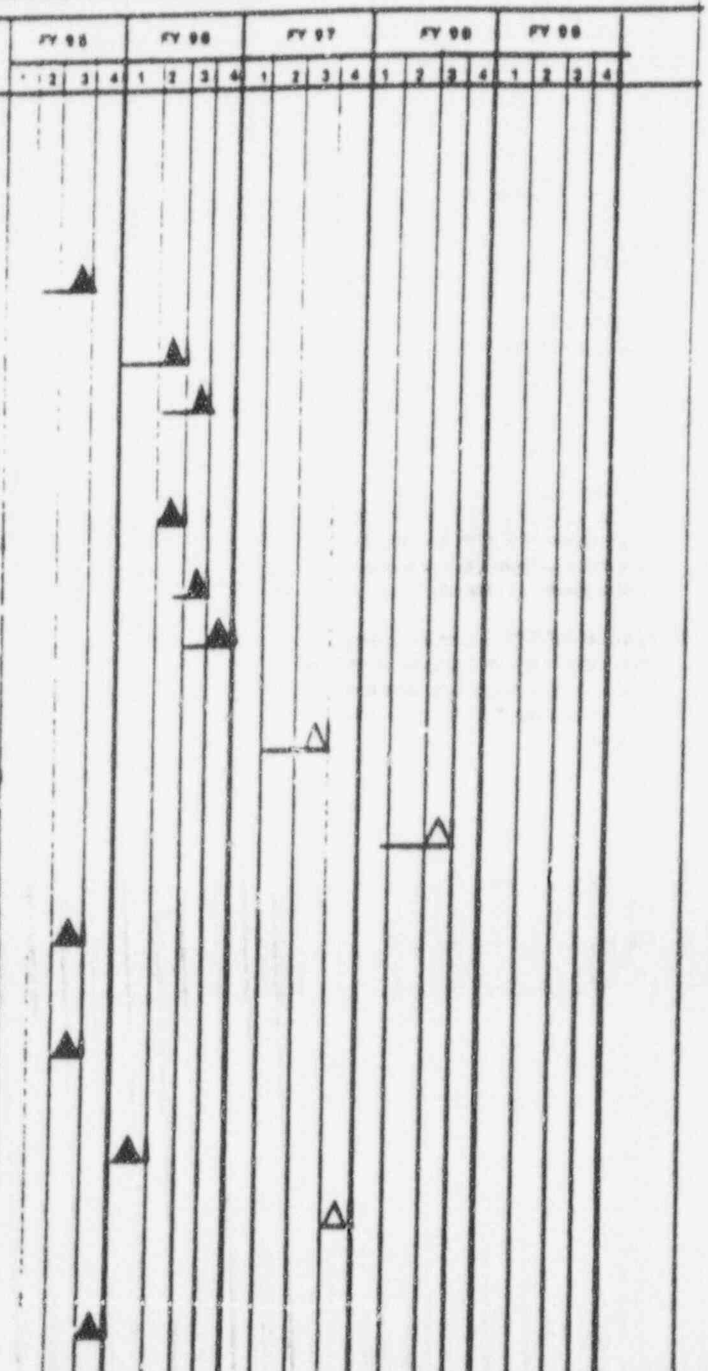
Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
H.4.3 Predictive Engineering Methodology																				
D. Define test matrix for cruciform validation tests that include pre-cleavage ductile tearing 1. specimen type, 2. crack geometry, 3. test temperatures, and loading conditions.									△											
E. Use data from validation tests (performed in Task H3) to perform analyses with FAVOR to confirm predictive capabilities, and modify methodology if necessary.												△								
F. Issue NUREG/CR report describing the methodology for inclusion of fracture-mode-conversion model in deterministic and probabilistic fracture mechanics analyses.												△								

NRC FORM 189 (Continued) (10-93) NRCMD 11.7	U.S. NUCLEAR REGULATORY COMMISSION DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK	JOB CODE B0119 DATE JULY 19, 1996
PROJECT TITLE:	Heavy Section Steel Technology	

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone — FY 95, FY 96, FY 97, FY 98, FY 99 (quarters 1 2 3 4)



H.5 FRACTURE ANALYSIS METHODS DEVELOPMENT AND APPLICATIONS

H.5.1 Continuing Development of FAVOR.

A. Generate SIFIC database for axially oriented semielliptical flaws for RPV with $(R_i/T) = 10$.

A.1 Implementation of SIFIC database into FAVOR.

A.2 Verification and Validation. Compare SIFIC database with those of other investigators where possible. Compare ABAQUS direct 3-D finite element and FAVOR solutions.

B. Generate SIFIC database for circumferentially oriented semielliptical flaws for RPV with $(R_i/T) = 10$.

B.1 Implementation of SIFIC data base into FAVOR.

B.2 Verification and Validation. Compare SIFIC database with those of other investigators where possible. Compare ABAQUS direct 3-D finite element and FAVOR solutions.

C. Implementation into FAVOR of correlation to include clad plasticity in fracture analysis. This correlation will be developed in Task 3.1.

D. Implementation in FAVOR of correlation to include fracture mode conversion effects in fracture analysis. This correlation will be developed in Task 4.3

E. Presentation and publication of a paper entitled: An Overview of FAVOR: A Fracture Analysis Code for Nuclear Reactor Pressure Vessels for the 1995 SMiRT conference.

F. Presentation and publication of a paper entitled: Validation of FAVOR Code Linear Elastic Fracture Solutions for Finite Length Flaw Geometries at the 1995 ASME Pressure Vessel and Piping Conference.

G. Presentation and publication at an appropriate forum on a paper regarding the SIFIC database.

H. Presentation and publication at an appropriate forum of a paper regarding the treatment of clad plasticity and clad fracture toughness into an RPV structural integrity assessment.

I. Release 9509 version of FAVOR to interested organizations active in RPV Safety Analysis.

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
H.5.1 <u>Continuing Development of FAVOR</u>																				
J. Update the FAVOR user manual to reflect the many changes since the last issuance of the user manual (1994). This is the FAVOR code that performs method 1 type of PTS analysis.												—	—	△						
K. Create user manual for FAVOR code that performs method 2 type of PTS analysis.												—	—	—	△					
L. Release latest version of FAVOR for performing method 1 type of PTS analysis to commercial and research organizations.														△						
M. Release latest version of FAVOR for performing method 2 type of PTS analysis.															△					

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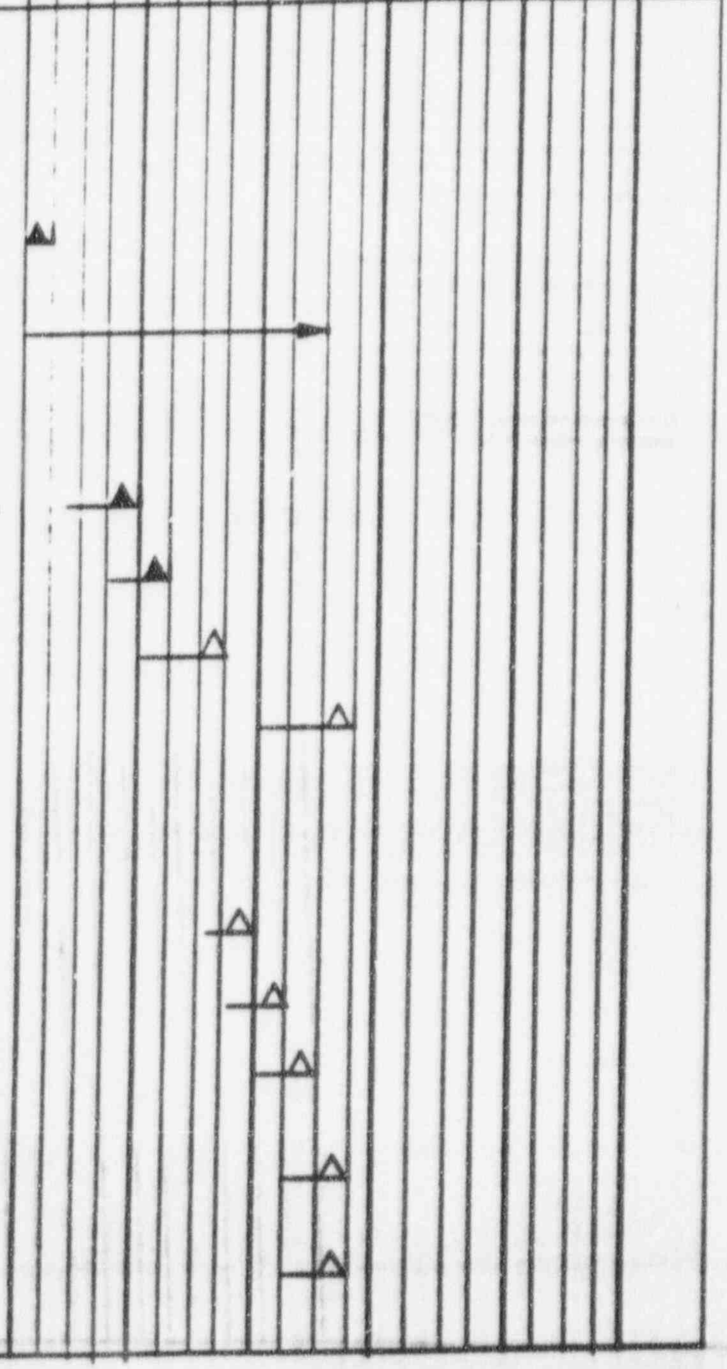
13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone — FY 95 (1 2 3 4), FY 96 (1 2 3 4), FY 97 (1 2 3 4), FY 98 (1 2 3 4), FY 99 (1 2 3 4)



H.5.2 PTS APPLICATIONS

H.5.2.A <u>Phase II Development Of Technical Bases And Methodologies For Revising Regulatory Guide 1.154</u>

a.1 Development of fracture mechanics model/ Publish letter report ORNL/NRC/LTR-94/31.

a.2 Interact with INEL, Sandia, and NRC to develop methodology for performing PFM uncertainty analysis.

a.3 Create FAVOR module to perform PFM uncertainty analysis.

a.3.1 Incorporate the capability to include thermal hydraulic uncertainty

a.3.2 Incorporate the capability to include embedded flaws.

a.3.3 Develop and implement FAVOR/PRODIGAL interface.

a.3.4 Implement Bayesian updating techniques developed by Sandia National Laboratories.

H.5.2.B <u>Phase III: Demonstration Analysis: Integration And Application Of Revised Technical Basis And Methodologies To Plant Specific Test Cases</u>

b.1 Perform "method 1" PFM analyses for H.B. Robinson.

b.2 Perform "method 2" PFM uncertainty analyses for H. B. Robinson.

b.3 Provide draft NUREG describing PFM technical bases development and results of PTS analyses for H.B. Robinson.

b.4 Provide final NUREG describing PFM technical bases development results of PTS analyses for H. B. Robinson.

b.5 Perform method 1 PFM analyses for plant 2 which is to be identified by the NRC.

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13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
H.5.2.B <u>Phase II: Demonstration Analysis: Integration And Applications Of Revised Technical Bases And Methodologies To Plant Specific Test Cases (Continued)</u>																				
2.6 Perform method 2 PFM analyses for plant 2 which is to be identified by the NRC										—	—	△								
2.7 Provide input to the NRC (for NUREG) with results of plant specific analysis for plant 2										—	—	△								
H.5.2.C <u>Review of PTS Screening Criteria</u>																				
2.1 Review the PTS screening criteria. Reconstruct models and analyses performed in SECY-82-465, from which current PTS screening criteria was derived		▲																		
2.2 Examine the impact on the PTS screening criteria of various model modifications.			▲																	
2.3 Perform probabilistic fracture analyses similar to those in Appendices G and H SECY-82-465, using proposed RG 1.154 revisions to fracture mechanics model, and RG 1.99, revision 2. Generate an updated plot of mean surface RTNDT versus mean frequency of failure, similar to Figure 1 of RG 1.154. Use the same transients as those in SECY-82-465			▲																	
2.5 Issue letter report reporting the results of the PTS screening criteria review performed in 5.2.C.1 - 5.2.C.[illegible]						▲														

13. (C) Schedule Information (Continued)

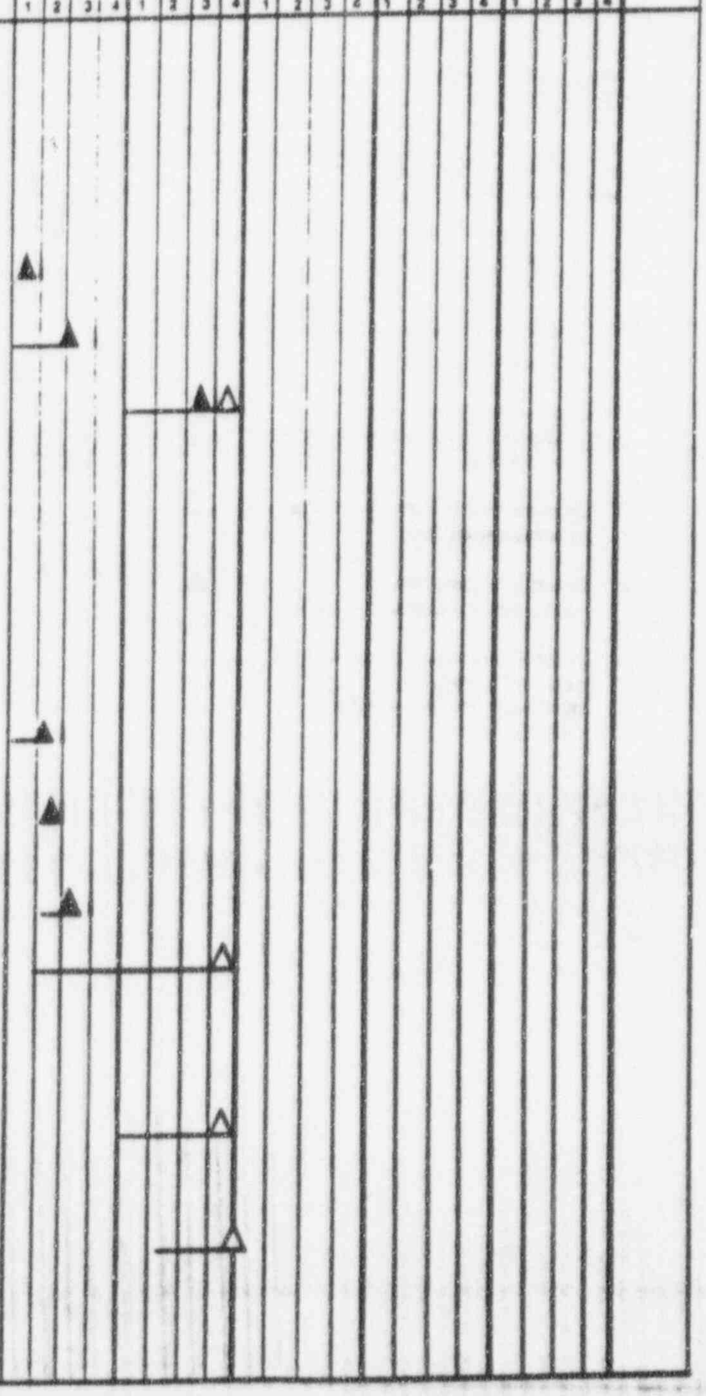
SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
H.5.2 PTS Applications (Continued)																				
H.5.2.D Perform value-impact analysis for the proposed revisions to RG 1.154.																				
a Data collection												△								
b Perform required analyses													△							
c Issue letter report on results of impact analysis														△						
H.5.3 NRC Technical Support																				
a Provide technical support to NRC staff during ACRS/CRGR reviews and public comment period	—	—	—	—	—	—	—	—	—	—	—	—	—	—	►					
b Provide support for NRC in Benchmarking and ASME Section XI Meetings	—	—	—	—	—	—	—	—	—	—	—	—	—	—	►					

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone — FY 95 (1 2 3 4), FY 96 (1 2 3 4), FY 97 (1 2 3 4), FY 98 (1 2 3 4), FY 99 (1 2 3 4)



H.6 MATERIAL PROPERTY DATA AND TEST METHODS

H.6.1 Ductile Fracture Toughness of Plate Materials (A302 Grade B)

A. Issue letter report with summary of test results.

B. Complete analyses of all fracture toughness tests.

C. NUREG/CR report with analyses of all test results.

H.6.2 Dynamic Fracture Toughness

Dynamic Fracture Initiation Toughness Test Data Generation

A. Prepare and ship test material.

B. Validation of test specimen, test facility, and test procedures.

C. Readiness review.

D. Complete testing program.

Test Data Interpretation and Toughness Determination

E. Prepare and issue test report.

Test Interpretation for Dynamic Initiation

F. Complete interpretive NUREG/CR report.

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
H.7 INTEGRATION OF RESULTS INTO A STATE-OF-THE-ART METHODOLOGY																				
H.7.1 Assessment of Analysis Methods to Current Regulatory Applications																				
A. Evaluate stress-intensity factor estimates for pressure, thermal loading and cladding.		▲																		
B. Evaluate uncertainty in applied K_I due to nonlinear biaxial effects.		▲																		
C. Evaluate cladding effects, including thickness, stress-relief and properties.		△																		
D. Evaluate residual stress effects due to welds and cladding.		△																		
E. Evaluate material property variability and uncertainty effects.		▲																		
F. Compile assessment of analysis methods for regulatory applications and issue summary NUREG.			△																	

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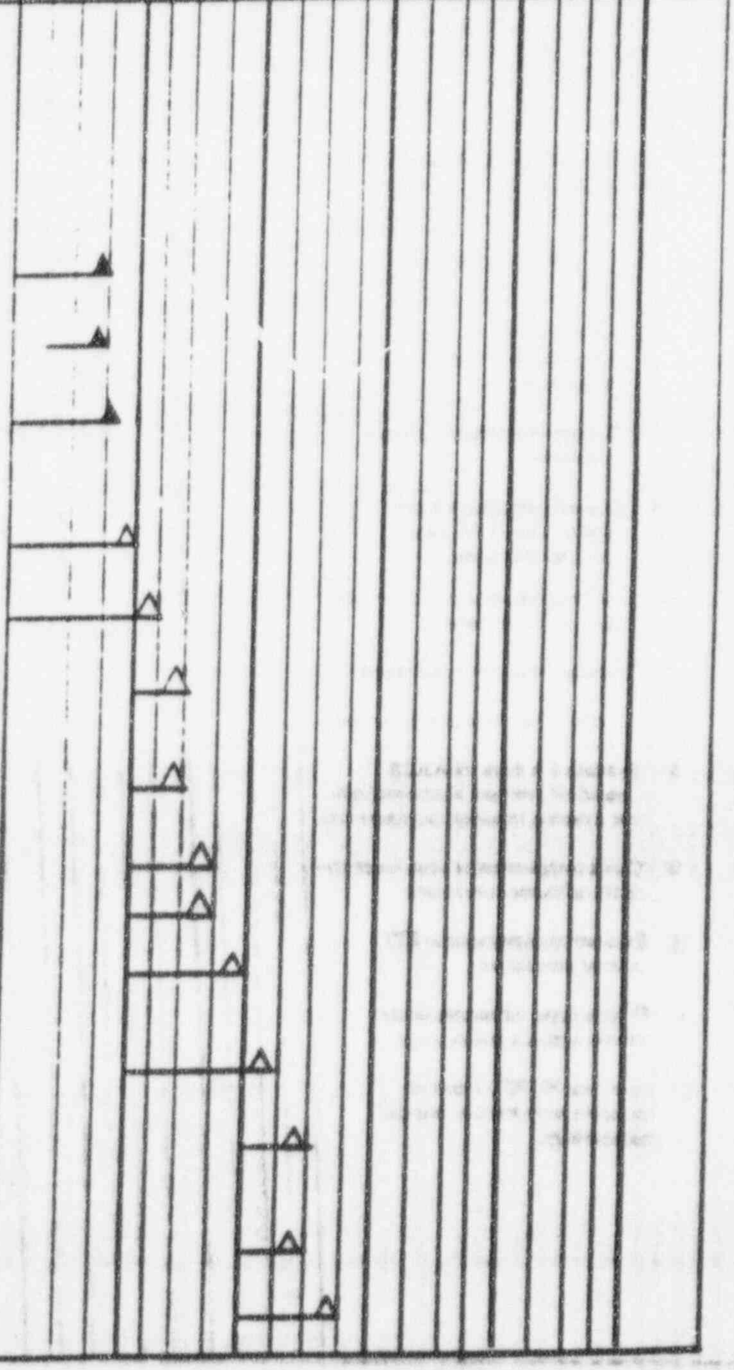
DATE: JULY 19, 1996

PROJECT TITLE: **Heavy Section Steel Technology**

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone — FY 95, FY 96, FY 97, FY 98, FY 99 (quarters 1 2 3 4)



H.7 INTEGRATION OF RESULTS INTO A STATE-OF-THE-ART METHODOLOGY (CONT'D)

H.7.2 Incorporation of Constraint and Other Research Results into a Fracture Analysis Methodology

A. Evaluate in-plane effects on toughness for shallow cracks.

B. Evaluate biaxial-loading effects on toughness for shallow cracks.

C. Interpret past HSST, NSWC, and NIST data with respect to constraint and strain gradient effects on toughness.

D. Develop interim proposed code methodology.

E. Compile evaluations and issue letter report.

F. Evaluate fracture toughness data from uniclad cruciform and full-thickness clad beam tests.

G. Evaluate biaxial and shallow-crack constraint analyses.

H. Evaluate clad yielding analyses.

I. Evaluate computational studies of fracture mode conversion.

J. Develop preliminary logic for comprehensive fracture analysis methodology.

K. Compile evaluations and issue letter report.

L. Evaluate fracture toughness data from medium-sized and large clad cruciform beams.

M. Evaluate improvements on constraint methodology.

N. Evaluate improvements in clad-yield analyses.

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PROJECT TITLE:	Heavy Section Steel Technology	

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

SUBTASK/MILESTONE

H.7 INTEGRATION OF RESULTS INTO A STATE-OF-THE-ART METHODOLOGY (CONT'D)

H.7.2 Incorporation of Constraint and Other Research Results into a Fracture Analysis Methodology (CONT'D)

O. Evaluate predictive mode-conversion model.

P. Improve logic for comprehensive fracture analysis methodology.

Q. Complete evaluations and issue letter report.

R. Evaluate additional fracture toughness data from unclad cruciform specimens.

S. Evaluate final version of constraint analysis methodology.

T. Evaluate final clad-yield model.

U. Evaluate final mode-conversion model.

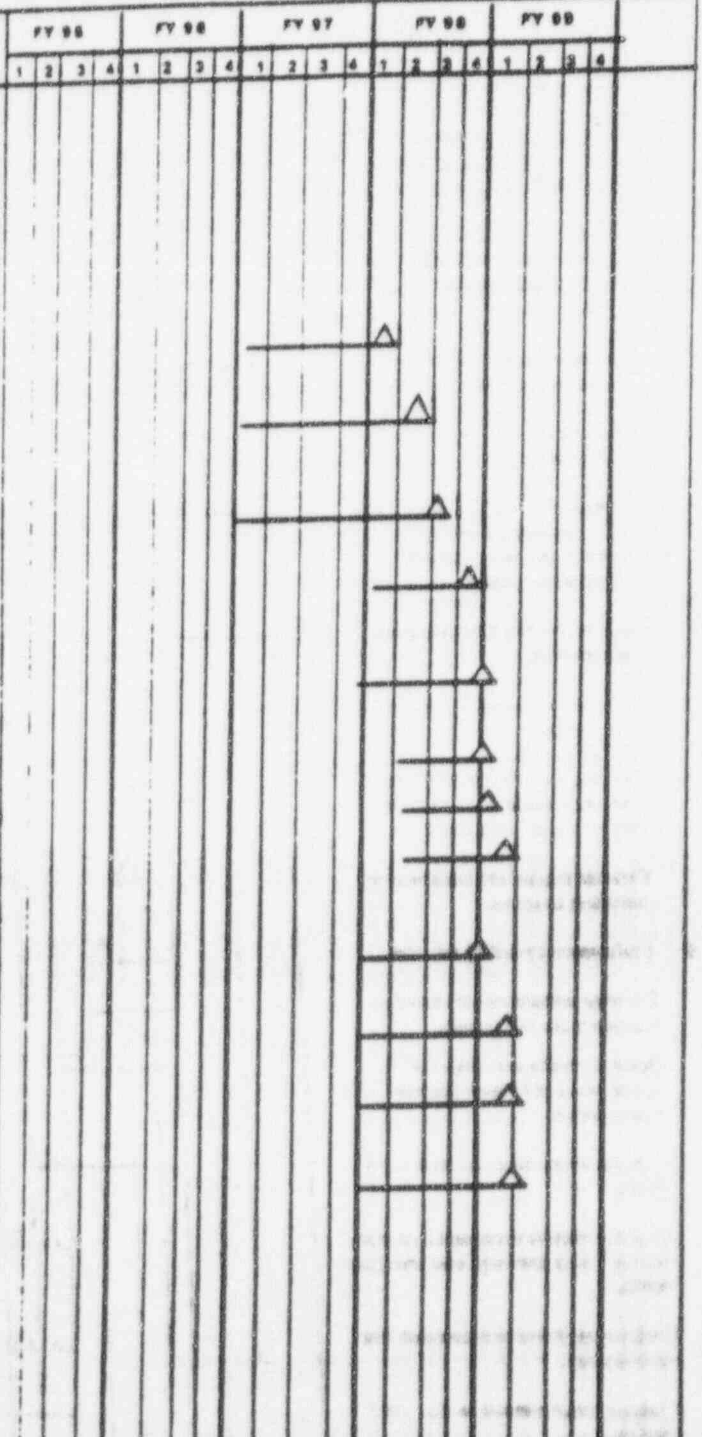
V. Evaluate J-R data for A302B (modified) steel and additional high-rate dynamic initiation toughness data.

W. Check completed set of stress-intensity-factor influence coefficients.

X. Evaluate improvements in PTS analysis procedures.

Y. Finalize logic for comprehensive fracture analysis methodology.

Z. Issue final NUREG report on comprehensive fracture analysis methodology.



U.S. NUCLEAR REGULATORY COMMISSION

DOE LABORATORY PROJECT AND COST PROPOSAL FOR NRC WORK

JOB CODE: B0119

DATE: JULY 19, 1996

PROJECT TITLE: Heavy Section Steel Technology

13. (C) Schedule Information (Continued)

SUBTASK/MILESTONE SCHEDULE

Subtask/Milestone	FY 95				FY 96				FY 97				FY 98				FY 99			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4

H.7 INTEGRATION OF RESULTS INTO A STATE-OF-THE-ART METHODOLOGY (CONT'D)

H.7.3 Participation in National and International Codes and Standards Organizations

A. Issue summary meeting report(s) 30 calendar days after each meeting on ASME Section XI fracture methodology development activities.

B. Issue summary meeting report(s) 30 calendar days after each meeting on ASTM Committee E-08 fracture methodology development activities.

C. Issue summary meeting report(s) 30 calendar days after each meeting with WRC PVRC Materials and Fabrication Division fracture methodology activities.

H.7.4 Special Technical Assistance

A. Presentation to ASME Section XI and PVRC.

B. Lead standard for measurement of fracture toughness in ductile-to-brittle transition with small specimens through the balloting process.

C. Provide assistance to NRC in resolving public comments on draft regulatory guide for low-Charpy upper-shelf materials.

D. Provide assistance to NRC in the evaluation of generic RPV integrity issues.

E. Provide assistance to NRC in the evaluation of the integrity of the RPV of the Palisades nuclear plant.

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(10-93)

NRCMD 11.7

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14. SPENDING PLAN
FY 1995

JOB CODE	B0119
MODIFICATION NUMBER (If applicable)	

NAME OF LABORATORY

Oak Ridge National Laboratory

PERFORMANCE PERIOD	
FROM	TO
10-01-94	12-31-98

TITLE OF PROJECT

Heavy Section Steel Technology

Total estimated costs of proposed project or modification at time of proposal submission: $10570k

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
DIRECT COST ($k)	126	223	158	118	227	262
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	126	223	158	118	227	262
PROJECT COMPLETION (%)	88.3	88.5	88.7	88.8	89.1	89.4

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
DIRECT COST ($k)	229	300	351	238	355	337
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	229	300	351	238	355	337
PROJECT COMPLETION (%)	89.6	90.0	90.4	90.7	91.1	91.4

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(10-93)

NRCMD 11.7

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14. SPENDING PLAN
FY 1996

JOB CODE
B0119

MODIFICATION NUMBER
(If applicable)

NAME OF LABORATORY
Oak Ridge National Laboratory

PERFORMANCE PERIOD

FROM	TO
10-01-94	12-31-98

TITLE OF PROJECT
Heavy Section Steel Technology

Total estimated costs of proposed project or modification at time of proposal submission: $10570k

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
DIRECT COST ($k)	183	229	240	206	229	286
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	183	229	240	206	229	286
PROJECT COMPLETION (%)	91.5	91.8	92.0	92.3	92.5	92.9

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
DIRECT COST ($k)	217	229	274	206	286	272
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	217	229	274	206	286	272
PROJECT COMPLETION (%)	93.1	93.4	93.7	93.9	94.2	94.5

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(10-93)

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14. SPENDING PLAN
FY 1997

JOB CODE	B0119
MODIFICATION NUMBER (if applicable)	

NAME OF LABORATORY

Oak Ridge National Laboratory

PERFORMANCE PERIOD	
FROM	TO
10-01-94	12-31-98

TITLE OF PROJECT

Heavy Section Steel Technology

Total estimated costs of proposed project or modification at time of proposal submission: $10570k

COST ELEMENT	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
DIRECT COST ($k)	130	162	170	146	162	203
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	130	162	170	146	162	203
PROJECT COMPLETION (%)	94.7	94.9	95.1	95.2	95.4	95.7

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
DIRECT COST ($k)	154	162	195	146	203	193
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	154	162	195	146	203	193
PROJECT COMPLETION (%)	95.8	96.0	96.2	96.4	96.6	96.9

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14. SPENDING PLAN
FY 1998

JOB CODE	B0119
MODIFICATION NUMBER (if applicable)	

NAME OF LABORATORY: Oak Ridge National Laboratory

PERFORMANCE PERIOD	
FROM	TO
10-01-94	12-31-98

TITLE OF PROJECT: Heavy Section Steel Technology

Total estimated costs of proposed project or modification at time of proposal submission: $10570k

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
DIRECT COST ($k)	118	147	154	133	147	184
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	118	147	154	133	147	184
PROJECT COMPLETION (%)	97.0	97.2	97.3	97.5	97.7	97.9

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
DIRECT COST ($k)	140	147	177	133	184	179
INDIRECT COST ($k)	0	0	0	0	0	0
TOTAL COST ($k)	140	147	177	133	184	179
PROJECT COMPLETION (%)	98.0	98.2	98.4	98.5	98.8	99.0

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(10-93)

NRCMD 11.7

U.S. NUCLEAR REGULATORY COMMISSION

14. SPENDING PLAN
FY 1999

JOB CODE: B0119

MODIFICATION NUMBER (if applicable):

NAME OF LABORATORY: Oak Ridge National Laboratory

PERFORMANCE PERIOD

FROM	TO
10-01-94	12-31-98

TITLE OF PROJECT: Heavy Section Steel Technology

Total estimated costs of proposed project or modification at time of proposal submission: $10570k

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH
DIRECT COST ($k)	310	310	300			
INDIRECT COST ($k)	0	0	0			
TOTAL COST ($k)	310	310	300			
PROJECT COMPLETION (%)	99.3	99.7	100.0			

ESTIMATED COST AND COMPLETION BY MONTH

COST ELEMENT	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
DIRECT COST ($k)						
INDIRECT COST ($k)						
TOTAL COST ($K)						
PROJECT COMPLETION (%)						

ROUTING AND TRANSMITTAL SLIP August 5, 1996

TO:

1.	[redacted]		
2.	BRANCH CHIEF: Michael Mayfield		
3.	DIVISION MA: Rita Hoskins		
4.	ROBERT PERCH, NRR - O-12-G18		

	Action		File		Note and Return
	Approval		For Clearance		Per Conversation
	As Requested		For Correction		Prepare Reply
	Circulate	X	For Your Information		See Me
	Comment		Investigate		Signature
	Coordination		Justify		

REMARKS

ENCLOSED IS A 189 DATED: July 19, 1996, Rev. No. 1

JOB CODE: B0119

PROJECT TITLE: Heavy Section Steel Technology

LAB: ORNL

FROM: Sue Decker	Bldg./Room No. T-10-D6
	Phone No. 415-6801