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Heavy-Section Steel Technology Program—Five-Year Plan FY 1983–1987

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75

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FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161

Available from
GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

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NUREG/CR-3595
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Dist. Category RF

Engineering Technology Division

HEAVY-SECTION STEEL TECHNOLOGY PROGRAM —
FIVE-YEAR PLAN
FY 1983—1987

Prepared by the Staff of the
Heavy-Section Steel Technology Program
Oak Ridge National Laboratory

Manuscript Completed — November 30, 1983
Date Published — April 1984

NOTICE This document contains information of a preliminary nature.
It is subject to revision or correction and therefore does not represent a
final report.

Prepared by the
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75

NRC FIN No. B0119

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
operated by
UNION CARBIDE CORPORATION
for the
U.S. DEPARTMENT OF ENERGY
under Contract No. W-7405-eng-26

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FOREWORD

The work reported here was performed at Oak Ridge National Laboratory (ORNL) under the Heavy-Section Steel Technology Program, C. E. Pugh, Program Manager. The program is sponsored by the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). The technical monitor for the NRC is Milton Vagins.

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ABSTRACT

The first in an annual series of five-year program plan documents is presented for the Heavy-Section Steel Technology program. The program is carried out by the Oak Ridge National Laboratory for the Materials Engineering Branch, Division of Engineering Technology, Office of Nuclear Regulatory Research of the U. S. Nuclear Regulatory Commission. The program is aimed at advancing the understanding and validation of materials and structures behavior as they relate to light water reactor pressure vessel integrity. The program has nine technical tasks and a management function. A background statement and a plan-of-action is given for each. The nine technical tasks address fracture methodology and analysis, materials characterization, crack growth, crack arrest, irradiation effects, cladding evaluations, intermediate-vessel testing, thermal-shock testing, and pressurized thermal-shock experiments.

1. INTRODUCTION AND OVERVIEW

1.1 Objective of Program Plan Document

This document is the first in a series that is to provide an up-to-date statement of the five-year plan for the Heavy-Section Steel Technology Program. The document is intended to be the reference document for management reporting during the forthcoming year. The forthcoming year for this edition is FY 1984. The program funding assumptions and the corresponding workscopes are responsive to guidance from the sponsor, the Materials Engineering Branch, Division of Engineering Technology, Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). This document augments other planning instruments, such as the Project and Budget Proposal for NRC work (189) in two important ways. First, milestone charts and plan-of-action statements can be presented here in detail without concern for space limitations. Second, this document can purposefully be drafted just prior to the beginning of the fiscal year, and thereby be a more accurate (timely) statement of the program plan for the forthcoming year than is possible with the schedule for some other documents, such as the 189.

This plan is a living document and is expected to be updated at the beginning of each year. The five years covered by the (current) plan are the current year (FY 1983), the forthcoming year (FY 1984), and three out-years (FY 1985 through FY 1987). Since a major objective is to provide a reference document for management reporting during the forthcoming year, that year is highlighted in the milestone charts and is emphasized in the plan-of-action sections. The subsequent years are described in a decreasing level of detail without loss of comprehensive coverage. A few identifiable events beyond FY 1987 are included for continuity. Also for continuity, the current year is included in detail, and the milestones that have been completed at the time of this writing are shown by filled symbols.

1.2 Objective of the HSST Program

The Heavy-Section Steel Technology Program (HSST) is carried out to advance the understanding and validation of materials and structures behavior as they relate to light water reactor pressure vessel integrity. The program had its beginning in the mid 1960's and has contributed to verifying the applicability of fracture mechanics to vessel integrity assessments, to advancing associated analysis tools, to data generation and correlations development, and to code criteria and rule development. The studies address the determination of the effects of flaws, variations in properties, stress raisers, and residual stresses on the integrity of vessels under combined thermal and mechanical loadings.

The program contains nine technical tasks in fracture methodology and analysis, materials characterization, crack growth, crack arrest, irradiation effects, cladding evaluations, intermediate-vessel testing,

thermal-shock testing, and pressurized thermal-shock experiments. The objectives of the various tasks combine to bear on the major issues relating to vessel integrity by providing improved techniques, data bases, and bases of validation. This interrelationship is illustrated by the situation of pressurized thermal-shock loadings where current advancements on fracture methodology and data bases combine with results from previous material and pressure vessel studies to give an assessment for conditions under combined thermal and pressure loadings.

The program budget has increased in recent years to accommodate more complex experiments and increased irradiation work. Concerning complex experiments, a test facility has been prepared for performing tests of pressurized intermediate vessels that are exposed to sharp thermal transients. The first such experiment (PTSE-1) is scheduled for early FY 1984, and a series of three tests is planned.

There is one remaining intermediate vessel for test under pressure-only loading (ITV-10), and it involves a nozzle-to-cylinder configuration and is tentatively scheduled for FY 1987. Thermal-shock test TSE-7 was completed in FY 1983 and involved a study of finite-length flaw behavior. Further thermal-shock tests are planned with TSE-8 to involve low upper-shelf weld material. Subsequent experiments with clad specimens are to be performed after results are available on the behavior of stainless steel cladding in irradiated conditions.

The major focus of the current irradiation work is on understanding the fracture characteristics of irradiated weld materials. The Fourth Irradiation Series includes four state-of-the-art weld materials that contain less than 0.12% copper. The Fifth Irradiation Series includes two high copper weld materials (Cu = 0.25 and 0.35%) and the Sixth Irradiation Series will be for stainless steel cladding.

1.3 Program Organization

A well-coordinated program has been in effect for more than fifteen years, and it has been instrumental in bringing the national technological base to its current status. The base includes national design codes (e.g., the ASME Boiler and Pressure Vessel Code), standards (e.g., ASTM Standards and USNRC Regulatory Guides), analysis methods, material properties data, and confirmatory structural behavior data. While the program has been mostly carried out at the Oak Ridge National Laboratory (ORNL), it has made use of subcontracted activities to take advantage of special expertise at other locations. The program has also been coordinated with other R and D programs sponsored by the NRC, DOE, EPRI, etc. National and international committee involvements have been maintained to help assure that existing technologies and data are employed and that developments are rationally sound and experimentally verified. In particular, the Pressure Vessel Research Committee (PVRC) and the NRC-appointed Vessel Integrity Review Group (VIRG) have played very important roles.

The program is presently composed of nine technical tasks and a management function. The organization of these tasks is illustrated in

the level 2 work breakdown structure for the program shown in Fig. 1.1. The tasks interface with each other and are augmented by documentation and technology transfer efforts. The remainder of this document is organized around this structure with a chapter addressing each technical task. The management task is addressed in the latter part of this chapter. A work breakdown structure has been developed for each task, and they are displayed in the corresponding chapters of this document. It is to be noted that those displays are actually work breakdown structures through level 3, with the fourth level (unnumbered) elements developed to illustrate the scope of work involved. In order to maintain a manageable level of detail, the milestones in each task are written under the level 3 elements of the work breakdown structure and not level 4. Each chapter also includes a brief objective statement for that task, a background discussion, and a plan-of-action section that augment the milestone charts.

1.4 HSST Task H.1 Program Management

1.4.1 Objective

The objective of Task H.1 is to effectively manage the technical tasks undertaken to address priority issues concerning LWR pressure vessel integrity in keeping with NRC approved plans. Management includes planning, integrating, monitoring, reporting, and technology transfer activities.

1.4.2 Background

The HSST program has been administratively carried out through the Engineering Technology Division of ORNL since its inception in the mid 1960s. A key part of that management function has been the integration of the technical objectives and the efforts of various program participants. The participants have included various divisions of ORNL, but most prominently the Engineering Technology and Metals and Ceramics Divisions, and several universities and industrial organizations through subcontracts. The aim has been and is to utilize capabilities and facilities in a complementing way to meet program objectives. The placement of the program within the ORNL organization is illustrated in Fig. 1.2, which also lists key staff members.

Concerning technical integration, a strong relationship has been maintained with peer groups and committees. These have included the Pressure Vessel Research Committee, ASME Code committees, ASTM Standard groups, and peer advisory groups. Their inputs on problems, priorities, and approaches have been factored into earlier program plans.*¹ In the most recent years, the NRC appointed Vessel Integrity Review Group (VIRG) has served a vital role in this regard, whereas in earlier years, the PVRC was similarly involved. A comprehensive review² was conducted

*References are listed in the end of each chapter of this document.

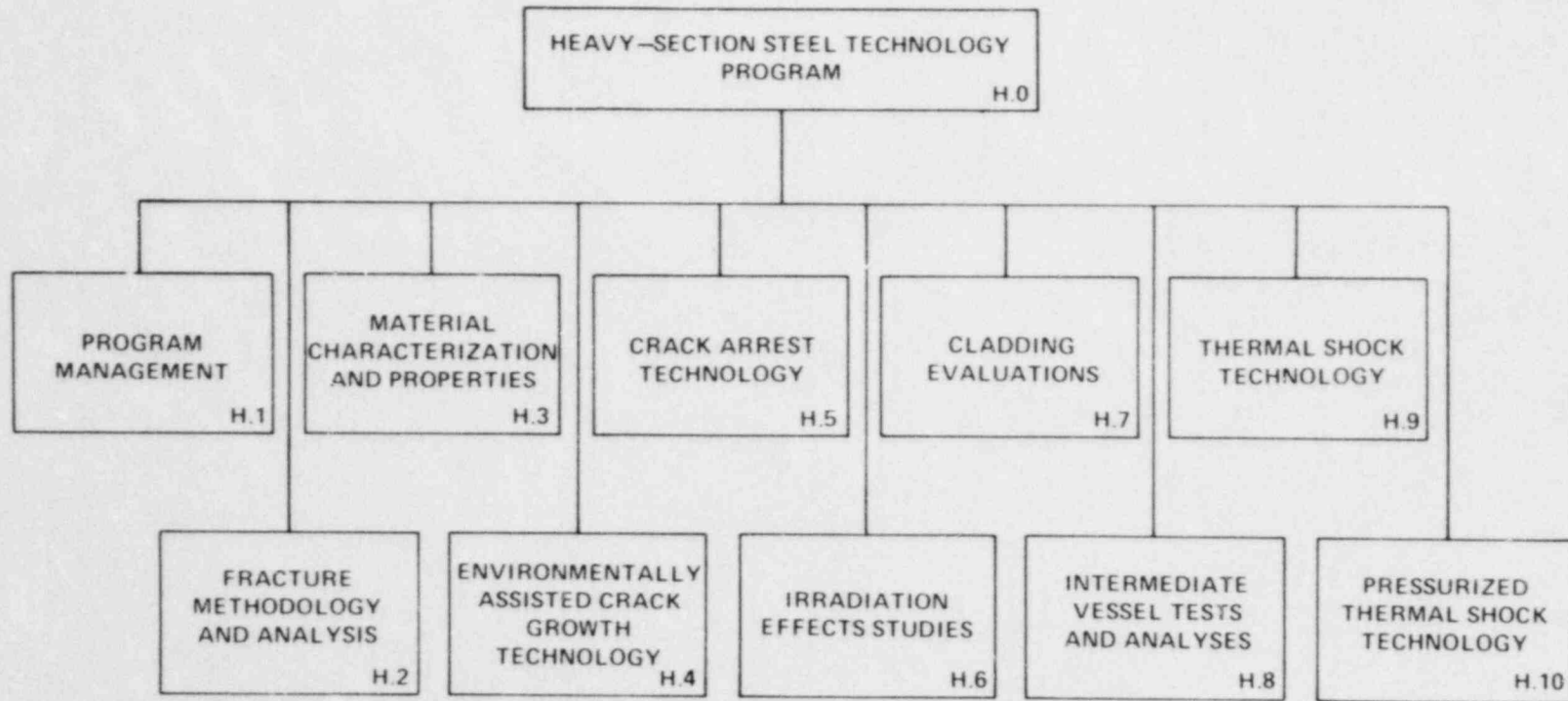


Fig. 1.1 Level 2 work breakdown structure for the Heavy-Section Steel Technology (HSST) program.

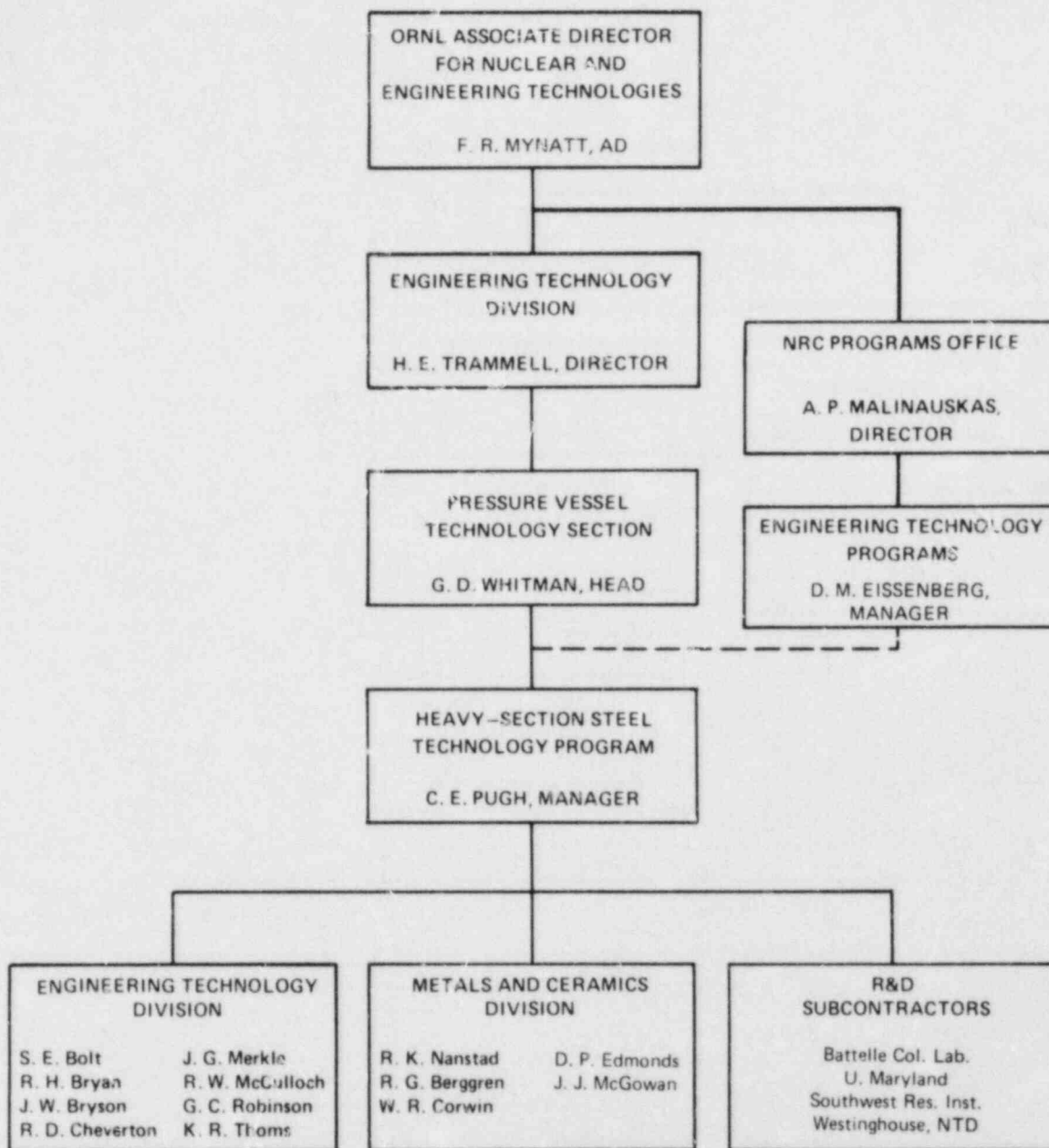


Fig. 1.2 Organization of the Heavy-Section Steel Technology program.

in the early stages of the program covering the current practice in RPV design, analysis, materials, fabrication, inspection, and testing. This review and the philosophy that it set in place have assisted in program integration. Additionally such reviews have provided the community with interpretive statements of the state-of-the-art.

Program developments have been transferred to the technical community through progress and topical reports, program review meetings, information meetings, open-literature papers, and committee participation. Technical interactions with foreign countries have been strong,

particularly with the European countries. Those countries have acknowledged the leading role that the HSST program has played in developing and verifying methods for assessing pressure vessel integrity.

1.4.3 Plan of Action

The plan for Task H.1 is to continue to manage the program through approved procedures. The level 3 work breakdown structure for this task is shown in Fig. 1.3. The three subtasks are continuations of the management functions that have historically been performed. The specific activities and schedules within the task are given in the following milestone chart. In addition to planning, monitoring, and reporting on the program performance in a timely manner, efforts will continue to be made to maintain effective technology transfer and to continue liaison with peer groups, committees, and programs in foreign countries.

This task will administer the research and development subcontracts and technical consulting arrangements that are required to supplement the ORNL work. The subcontractor reports are integrated into the overall program quarterly progress reports. For example, see the FY 1983 progress reports (Refs. 3-6). The financial burden of progress report

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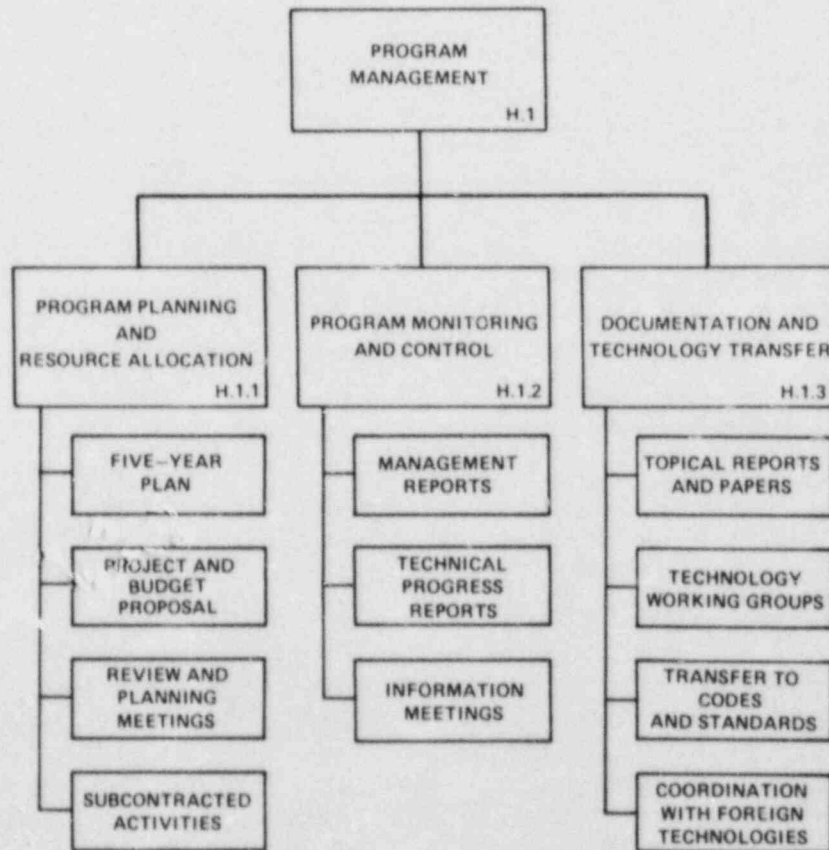


Fig. 1.3 Work breakdown structure for the HSST Task H.1 Program Management.

publication, all consultants, and program office administration will be born by this task.

Beginning with FY 1984, a revised management reporting system will be employed. This will include monthly reports from the ORNL program manager to the NRC program manager that have six parts, (1) a meeting and travel report, (2) a description of technical accomplishments, (3) schedule deviations and impact statements, (4) an identification of anticipated problems, (5) a list of publications and (6) a financial report. An associated part of this reporting procedure is the preparation of an annual edition of the program's five-year plan. The plan will be issued near the end of each fiscal year and will serve as the reference plan document during the next year.

The coordination of technologies with foreign countries often leads to cooperative efforts and assignment of personnel between the various countries. Concerning cooperative efforts, the international round-robin on precracked Charpy testing (Task H.2) will be completed in FY 1984 and irradiation and testing of a reactor vessel steel from West Germany will also be carried out in FY 1984 (Task H.3). The program has an invitation to participate in analyzing West Germany's HDR nozzle corner cracking test results and in the planning and analysis of the Pressurized Thermal Shock Test of the HDR beltline region after insertion of an axial flaw. Especially, the latter of these invitations is attractive to the HSST program; but they were not included in the present plans due to budgetary restraints.

With regards to the exchange of personnel, Dr. Shafik Iskander of ORNL is to continue his assignment as the NRC representative to the MPA in the FRG through FY 1984 (funded under a separate FIN number). A representative (Dr. Keith Reading) from the UKAEA-Risley is to be on assignment to ORNL for the first seven weeks of FY 1984 to work with the thermal-shock task (Task H.9). Dr. Reading is the principal investigator for the UKAEA spinning disc thermal-shock testing program. It is anticipated that a representative (Dr. H. Stamm) from the Institute für Reaktorbauelemente, Karlsruhe, is to be assigned to ORNL for three months in late FY 1984. Also Dr. Wanner of the Swiss Federal Institute for Reactor Research is expected to request a one-year assignment to ORNL beginning in the second half of FY 1984. These latter two individuals are analysts working with fracture computer programs such as ADINA and would be working in that area during assignments to ORNL. They both will be participating for their respective organizations in the analysis of the HDR experiments performed in West Germany.

1.4.4 References

1. G. D. Whitman et al., *Program Plan — The Heavy-Section Steel Technology Program*, February 27, 1970, Rev. 0, April 1, 1968, Rev. 1, (prepared for the USAEC).
2. G. D. Whitman, G. C. Robinson, Jr., and A. W. Savolainen, *Technology of Steel Pressure Vessels for Water-Cooled Nuclear Reactors*, ORNL-NSIC-21, December 1967.

3. G. D. Whitman, C. E. Pugh, R. H. Bryan, *Heavy-Section Steel Technology Program Quart. Prog. Rep. October-December 1982*, NUREG/CR-2751, Vol. 4, (ORNL/TM-8369/V4).
4. C. E. Pugh, *Heavy-Section Steel Technology Program Quart. Prog. Rep. January-March 1983*, NUREG/CR-3334, Vol. 1 (ORNL/TM-8787/V1).
5. C. E. Pugh, *Heavy-Section Steel Technology Program Quart. Prog. Rep. April-June 1983*, NUREG/CR-3334, Vol. 2 (ORNL/TM-8787/V2).
6. C. E. Pugh, *Heavy-Section Steel Technology Program Quart. Prog. Rep. July-September 1983*, NUREG/CR-3334, Vol. 3 (ORNL/TM-8787/V3).

1.4.5 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.1 are given in the following charts.

The symbology used in all the milestone charts in this plan and in the HSST program management reports is given in Fig. 1.4 below. The "n" over of the symbols designates the calendar month when a schedule change is made.

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MILESTONE SYMBOLOGY











	Starting date
	Intermediate Milestone
	Intermediate Milestone Completed
	Major Milestone
	Major Milestone Completed
	Rescheduled Milestone
	Rescheduled Milestone Completed
	Revised Milestone
	Revised Milestone Completed
	Milestone Deleted

Fig. 1.4 Milestone chart symbology.

Task: H.1 PROGRAM MANAGEMENT		MILESTONE STATEMENT AND SCHEDULE																							
		FY 83		FY 1984												FY 85				FY 86	FY 87	Beyond FY 87			
		1	2	3	4	0	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
<u>SUBTASK/MILESTONE</u>																									
H.1.1 <u>Program Planning and Resource Allocations</u>																									
A. Issue Five-Year Plan																									
a. Issue FY-1984 edition																									
b. Issue FY-1985 edition																									
c. Issue FY-1986 edition																									
d. Issue FY-1987 edition																									
B. Issue Project and Budget Proposal (189)																									
a. Issue preliminary 189 for budget cycle																									
b. Issue final 189 for workslope																									
C. Select and Administer Subcontract Activities on an Annual Basis																									
H.1.2 <u>Program Monitoring and Control</u>																									
A. Issue Monthly Management Reports (by the end of subsequent month)																									
B. Issue Quarterly Technical Progress Reports																									
C. Participate in NPC Annual Information Meetings																									

MILESTONE STATEMENT AND SCHEDULE

Task: H.1 PROGRAM MANAGEMENT (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
H.1.3 <u>Documentation and Technology Transfer</u>																									
A. Coordinate Issuance of Topical Reports and Papers																									→
B. Maintain Membership on ASME, ASTM, and International Cyclic Crack Growth Committees																									→
C. Exchange Technology with Foreign Countries as Approved by NRC-NRR																									→

2. HSST TASK H.2 FRACTURE METHODOLOGY AND ANALYSIS

2.1 Objective

The objective of Task H.2 is to develop and evaluate the experimental data and methods of analysis by which the fracture toughness of reactor pressure vessel (RPV) steels can be reliably determined and the results applied with confidence to the design and safety analysis of nuclear vessels.

2.2 Background

The activities covered by this task have generally been and are now organized according to the work breakdown structure shown in Fig. 2.1. The approach has been to assess the applicability of fracture strength methods, with initial methods being based on linear-elastic fracture mechanics, to nuclear vessels on the basis of experimental validation. The HSST Program was the first research effort specifically concerned with high-toughness structural materials that recognized the need for elastic-plastic methods of calculating fracture toughness and analyzing cracked structures. The preceding COD methods considered only crack tip yielding and did not involve elastic-plastic stress analysis. At the outset it was recognized that direct as well as numerical analysis procedures are required, and that experimental programs are vital to the development as well as the validation of analysis methods. The following paragraphs address some of the background in terms of the four sub-tasks shown in Fig. 2.1.

2.2.1 Fracture Toughness Determinations and Strength Methods

2.2.1.1 Small specimen fracture toughness in the cleavage range. On the basis of the large specimen sizes that had to be used to measure LEFM valid values of fracture toughness¹ for HSST Plate 02, it was clear that specimens small enough to be used routinely for material characterization would yield before fracturing. Therefore, early in the program, semiempirical methods,^{2,3} and correlations⁴ were developed for estimating fracture toughness values from specimens of limited size for the design and analysis of the intermediate test vessels. Following the initial multi-specimen experimental applications⁵ of the J Integrals⁶ for measuring fracture toughness, the HSST Program contributed to the development of single specimen equations applicable first to the notched beam⁷ and then to the compact specimen.⁸ The latter analysis is now the basis for the measurement of J Integral resistance curves for structural and pressure vessel steels.⁹

Although the existence of size effects in the measurement of fracture toughness has been known for some time, the dependence of these effects on specimen geometry, loading rate, and fracture mode has not been clear, nor the effects consistently recognized. The large scatter

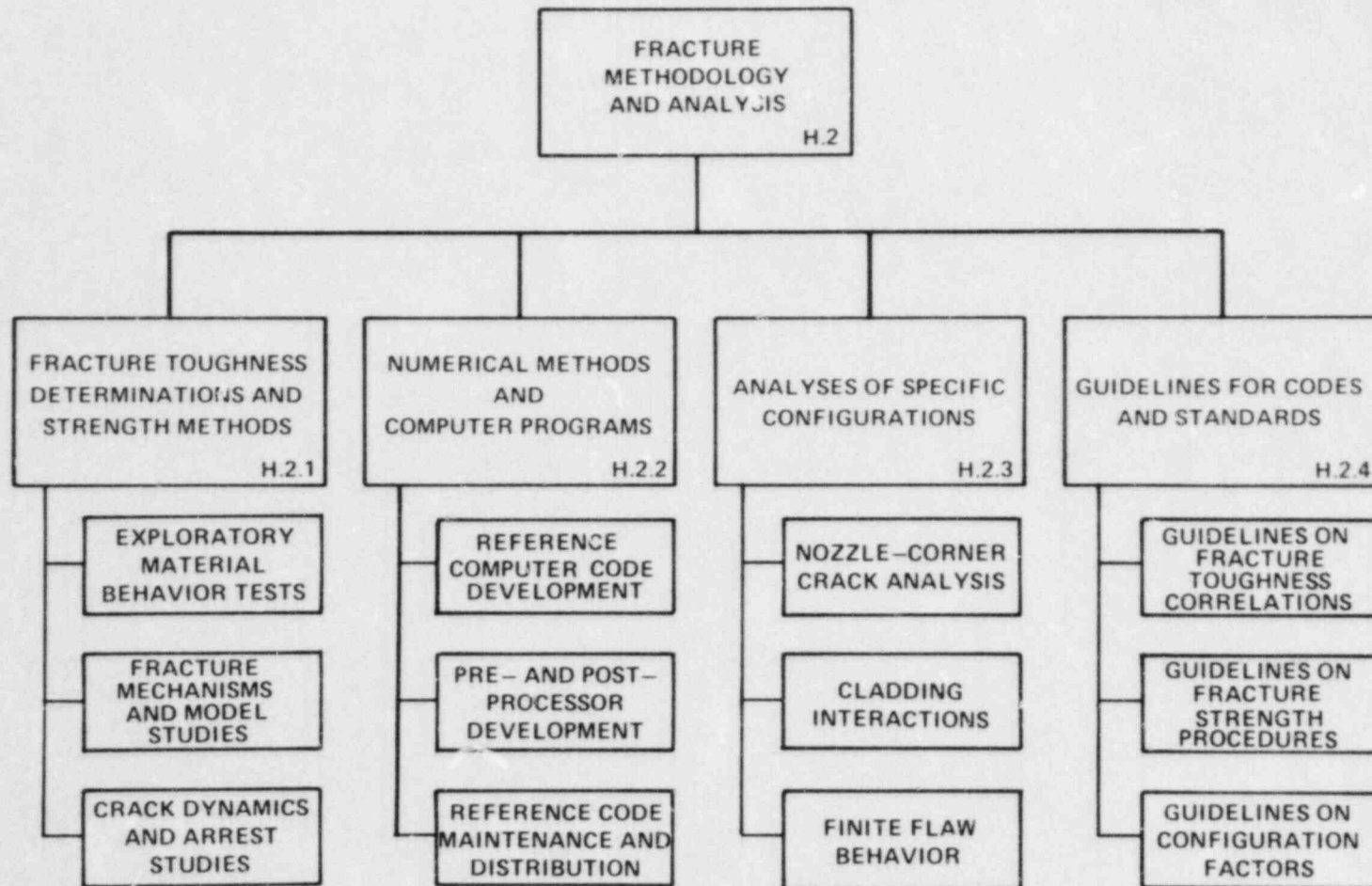


Fig. 2.1 Work breakdown structure for the HSST Task H.2 Fracture Methodology and Analysis.

in data and elevation of small specimen toughness values with respect to large specimen test results^{10,11} for TSE-5 and TSE-5A brought this problem to focus, and motivated a deliberate study of the problem.¹² It turns out that a semiempirical method of analysis developed by Irwin¹³ in 1960 can be applied to this problem, but that a better understanding of the physical basis for size effects is necessary to justify the application of such a procedure to important problems involving structural safety. The method, as refined by ORNL, is currently being applied to the toughness characterization of the vessels scheduled to be used for future thermal-shock and pressurized thermal-shock tests.

Resistance curve measurements of ductile-tearing toughness currently require the measurement of small amounts of crack extension by somewhat difficult means. This requirement thwarts the use of load-displacement data from specimens not instrumented for Δa measurement for estimating resistance curve values. A method of estimation based only on load-displacement measurements recently developed under the fracture mechanics task helps to circumvent this difficulty.¹⁴ In addition, the proper application of a correction to the J calculation for stable crack extension during an R curve test has a strong effect on the size independence of the resulting R curve and the toughness level implied by the data. An improved correction has been developed by Ernst,¹⁵ and a direct derivation, based on physical reasoning, has been developed and implemented at ORNL, facilitating the direct application of the improved correction to new experimental data.

In the temperature range within which cleavage is the dominant mode of fracture, an increase in loading rate or crack speed tends to lower the toughness toward a minimum level. However, fast running cracks eventually display an increase in toughness with crack speed implying the interaction of multiple physical phenomena. A preliminary analysis has been developed that implies that the observed minimum is the result of the opposite effects of strain rate and entrapped heat in the crack tip plastic zone. This hypothesis will be investigated further, because it offers the possibility of estimating the crack arrest toughness from other more easily measured properties.

2.2.1.2 Cleavage-fibrous transition investigations. The University of Maryland, under UCCND Subcontract, has been investigating the physical and metallurgical basis for the conversion of fracture mode with temperature from cleavage to fibrous tearing. This investigation utilizes and extends previous observations of cleavage microcracking¹⁶ and ductile remaining ligaments,¹⁷ and has provided direct supporting information for the study of size effects in cleavage fracture toughness testing (Milestone H.2.1.A). Improved methods of etching and crack profile measurement have been developed, and they promise to facilitate the obtaining of metallurgical information specific to reactor grade steels. An effort has also been underway at Battelle Columbus Laboratories,¹⁸ under UCCND Subcontract, in coordination with the work at the University of Maryland.

2.2.1.3 Precracked Charpy V-notch (PCCV) round robin. Because of the need for reliable small specimen testing methods (Milestone H.2.1.A) and because of periodic proposals and problems concerning the use of PCCV specimens, a meeting on the subject was held at EPRI in December 1980, sponsored by CSNI.¹⁹ The NRC proposed at that meeting that the

HSST Program furnish PCCV specimens from the TSE-5A cylinder for an international round-robin test program. Eleven laboratories, including ORNL, volunteered to test specimens. To date ORNL and six other laboratories have delivered results, all consistently indicating the same large degree of scatter and upward elevation of toughness values in the transition range. A final evaluation of data received will be performed in FY 1984.

2.2.2 Analysis Methods and Computer Programs

2.2.2.1 Computer code development. Both general and special-purpose computer programs are being developed for use in HSST fracture studies. Table 2.1 gives the status and capabilities of each of the fracture codes developed at ORNL. These programs perform static analysis of brittle or ductile fracture in 2-D or fully 3-D crack geometries. In addition, the SAMCR dynamic fracture analysis code has been developed under subcontract to the University of Maryland; and the dynamic fracture code FRACTDYN has been utilized through a subcontract with Battelle Columbus Laboratories. SAMCR (Stress Analysis of Moving Cracks) has been used to perform posttest analyses of TSE-5, with limited success.²⁰ Improvements have recently been made to the program,²¹ which should lead to improved results and an independent capability to check on the static results obtained with the OCA code at ORNL (see Task H.9) and the dynamic results obtained with the FRACTDYN code by Battelle Columbus Laboratories.²²

The OCA series of codes and the ORVIRT-ADINA finite element system have been extensively applied in the design of HSST experiments. The OCA codes employ a cost-effective influence function approach which when coupled with their outstanding post-processing capabilities make them particularly suitable for parametric studies. With the exception of OCA/USA which has an upper-shelf analysis capability, and a direct ligament stability analysis, the OCA codes are linear elastic and limited to the analysis of surface flaws in PWR or ITV geometries. The ORVIRT-ADINA finite element system represents a more general capability, and is a fully 3-D thermo-elastic-plastic finite element system which uses a virtual crack extension technique for the computation of energy release rates at various points along the crack front. Special crack tip elements are employed which introduce the appropriate stress singularity.

2.2.2.2 Direct analysis techniques. Up to the present time, the analysis of pressurized thermal-shock events in reference model vessels have been performed by elastic analysis, e.g., with the OCA Code.²³ However, direct analyses have been used to show that as the crack becomes deep, the remaining ligament yields under combined bending and tension, causing additional crack opening displacements. Under pressure loading, a crack depth is subsequently reached at which the remaining ligament is yielded under uniform tension, causing large additional crack opening displacements which would eventually lead to ligament necking and tensile instability.²⁴ The analysis of this phenomenon for an external crack has been included in a modification of the OCA code called OCA/USA²⁵ (OCA Upper-Shelf Analysis), and is being used in the pretest analysis of PTSE-1 (see Task H.10).

Table 2.1. Summary of HSST computer programs for fracture analysis

Fracture code	Date developed	Numerical method	Geometry	Nonlinear material behavior	Comments
<u>ORNL Developed Fracture Codes</u>					
OCA/USA	Under development	Influence function	2-D, limited 3-D	Limited	An enhanced version of OCA-II, designed primarily for pressurized-thermal shock experiments
OCA-P	June, 1983 NUREG/CR-3618 ORNL-5991	Influence function, Monte Carlo	2-D, limited 3-D	No	Probabilistic fracture code employing a Monte Carlo simulation technique
OCA-II	May, 1983 (Report in preparation)	Influence function	2-D, limited 3-D	No	Outstanding post-processing capabilities, especially suitable for parametric analyses of surface flaws in PWR and ITV geometries
ORVIRT	February, 1983 NUREG/CR-2997 Vol. 2 ORNL/TM-8527/V2	Finite element (Virtual crack extension)	2-D, 3-D	Yes	Versatile and powerful fracture code, interfaces with ORMGEN and ADINA
ORMGEN	December 1982 NUREG/CR-2997 Vol. 1 ORNL/TM-8527/V1	Finite element mesh generator	3-D	N/A	Generates a 3-D finite element model for cracked plates or cylinders in an ADINA compatible format
ORFLAW	April, 1982 NUREG/CR-2494 ORNL/CSD/TM-165	Finite element (Embedded K)	3-D	No	Developed under subcontract to S. Atluri, Georgia Tech, 3-D, linear elastic only, automatic mesh generation
OCA-I	August, 1981 NUREG/CR-2113 ORNL/NUREG-84	Influence function	2-D	No	Strictly 2-D analysis of surface flaws in PWR and ITV geometries
NOZFLAW	March, 1981 NUREG/CR-1843 ORNL/NUREG CSD/TM-18	Finite element (Embedded K)	3-D	No	Developed under subcontract to S. Atluri, Georgia Tech. Addresses nozzle corner flaws only, automatic mesh generation
FMECH	February 1981 NUREG/CR-1499 ORNL/NUREG/CSD/ TM-14	Finite element (Virtual crack extension)	2-D	No	First ORNL developed code, limited capabilities relative to more recently developed codes
<u>Outside Codes that Interface with ORNL Computer Programs</u>					
BIGIF	1978 EPRI RP-700-1	Influence function	2-D, limited 3-D	No	Developed under EPRI sponsorship, widely used by utilities
ADINA	1975 (rev. 1978) MIT report 92448-1	Finite element	2-D, 3-D	Yes	A general purpose finite element code for structural analysis developed by K. J. Bathe at MIT

2.2.3 Analysis of Specific Configurations

At the outset of the HSST Program it was recognized that the development of fracture mechanics estimating methods for finite length through and part-through surface cracks subject to stress gradients would be an important part of the fracture mechanics task. In fact, the realism and practical applicability of the experimental and analytical results of the HSST program were seen to depend significantly on this factor. Numerical methods were not capable of treating this problem with sufficient speed or accuracy, so semiempirical methods were developed. These methods still prove extremely useful for preliminary estimates, experimental design and the definition of problems for numerical analysis by methods that are now much improved (see the completed Milestone H.2.2.D.a).

An experimental approach to the problem for inside nozzle corner flaws was taken, based on the fracture testing of epoxy scale model vessels.²⁶ Three-dimensional photoelastic studies^{27,28} and analytical studies²⁹ followed. Some differences between these results, with respect to K_I variations around the flaw perimeter for deep cracks, still remain to be resolved.²⁹

The burst analysis of through flawed cylinders utilized semiempirical equations developed at Battelle Columbus Laboratories, for which rational derivations were developed at ORNL.³⁰ These analyses need to be augmented for the purpose of estimating flaw opening areas and leak rates for through flaws, a problem concerning which assistance is being provided to Pacific Northwest Laboratories.

The work on the finite length part-through surface crack subject to a stress gradient began with a review of existing solutions and estimates,³¹ followed by the development of a semiempirical equation adjusted to fit three-dimensional photoelastic experimental data.³² A preliminary version of this equation was used for the initial ORNL study of the thermal-shock problem,³³ and later for the design and analysis of the two thermal-shock experiments involving finite length part-through surface cracks,^{34,35} TSE-2 and TSE-7. It was also used for the posttest analysis of the V-8 Test,³⁶ the flaw design and pretest ductile-tearing instability analysis of the V-8A test,³⁷ and the design of the flawed stainless steel clad plate tests³⁸ (see Task H.7). In the latter case a method was developed whereby the shape of arrested cracks propagating in a region of stress and toughness gradient can be estimated. This aspect of the method will be further explored.

In the posttest analysis of the V-8 Test,³⁶ it was noticed that the back face free surface magnification factor found to be appropriate for a flawed plate produces an overestimate of K_I for a deep crack in a cylinder, because of the circumferential continuity of the cylinder. The use of a different magnification factor based on no change in back surface curvature was found to remedy this problem.³⁶

In studying a question concerning the shortest length of a surface crack that could be treated as a continuous crack, for PTS experimental design, it became evident that a considerable difference in K_I values exists between finite length and continuous cracks in pressurized cylinders, for $a/W > 0.5$. This is because bending stiffness is not lost beyond the ends of the crack for a finite-length crack. This investigation led directly to the consideration of finite-length flaw effects in PTS analysis³⁹ (see Tasks H.9 and H.10).

2.2.4 Guidelines for Codes and Standards

2.2.4.1 Fracture-toughness correlations. Current specifications do not require the measurement of complete curves of fracture toughness versus temperature for reactor vessel steels. Therefore correlations are needed in order to facilitate the construction of such curves, which are necessary for performing safety analyses, especially for loadings involving thermal transients. The HSST Program has contributed several useful correlations between impact data and fracture toughness,^{4,40,41} as well as the valid data^{1,42} on which the present ASME Section III and Section XI reference fracture-toughness curves are based.^{43,44}

The HSST Program continues to participate in efforts to develop improved impact energy-toughness correlations, principally through active membership in the PVRC/MPC Task Group on Reference Toughness. This group is currently evaluating the applicability of a statistically augmented correlation between Charpy-impact energy and fracture toughness, based on curve fitting with a hyperbolic tangent equation.⁴⁵ ORNL has contributed directly to clarifying the mathematical basis of the method, as well as pointing out size effects between the EPRI ITCT toughness data base and the large specimen data for Plates 02 and 03. Another problem remains regarding the inability of the method to make consistently accurate predictions of mean values, despite the statistical nature of the method. Additional attention to these problems will be required. We have also participated in the deliberations of ASTM Committee E-24 on Fracture-Toughness Testing concerning the proper application of Equivalent Energy procedures, again pointing out the existence of size effects so as to make the description of the procedure accurate and acceptable. These efforts will continue.

2.2.4.2 Fracture strength (analysis) procedures. The development of strength analysis methods applicable to flawed regions in pressure vessels that consider strain gradients and inelastic behavior has been a focal point of the fracture mechanics task since its beginning. As stated earlier, the development of direct as well as numerical iterative methods of analysis has been a guideline within the task. This approach recognizes the existence of cost and time limitations, the need to determine the significance of specific variables, the need for considering flaw size as a dependent variable in experimental design, the need for independent checks, and the fact that numerical methods are not specified in the ASME Code. Pre and posttest analyses of intermediate vessel tests were solicited from others, and made at ORNL, using as many different methods as could be identified and shown to be applicable to the problem.⁴⁶⁻⁴⁸ Two of the earliest methods of analysis developed were the Equivalent Energy⁴⁹ method and the Tangent Modulus⁵⁰ method, the latter of which was originally semiempirical and based on experimental results from surface flawed bars tested to fracture in the elastic-plastic range.⁵¹ Although controversial for some time, the Equivalent Energy method was eventually shown to be relatable to the J Integral, on the basis of an assumed power law stress-strain curve.⁵² Furthermore, an extension of this approach resulted in the development of the British Normalized COD Design Curve, thus relating three originally separate fracture analysis procedures.⁵³ The Tangent Modulus method was subsequently derived theoretically from the J Integral, via the development of an incremental form of Neuber's equation for calculating inelastic stress and strain concentration factors.⁵⁴

In addition to fracture mechanics analyses, it was also necessary to develop direct methods of calculating or estimating the nominal elastic-plastic pressure versus strain curves for vessel cylinders⁴⁷ and nozzle corner regions.⁵⁵ The former is an exact solution for a tri-linear stress-strain curve, and the latter is semiempirical. Both estimates are used to judge the detail necessary for representing the stress-strain curve in a numerical analysis, and the accuracy of the results.

Eventually, a load will be reached at which a flawed structure will fail by necking and tensile instability due to the reduction of load-bearing area caused by the flaw. An analysis of this phenomenon was developed for a part-through surface crack in a vessel cylinder,⁴⁶ and it continues to prove useful in analyses such as those for pressurized thermal shock.

It turns out that two of the most difficult fracture mechanics tests to analyze over the entire range of load from elastic to fully plastic are the surface cracked tensile bar and the inside nozzle corner crack. The only analysis method that has so far been successfully applied to both, as well as an ITV cylinder, is the Tangent Modulus method.^{50,55,56} The complications in the data are due to such factors as the effects of incremental yielding, transverse contraction, net section eccentricity, strain gradients, and tensile instability. Given the opportunity, numerical methods will be applied to these problems, because they constitute a severe test of the generality of analytical methods.

An important aspect of the HSST Program has been the interpretation of the experimental and analytical results with respect to the expected performance and safety margins of reactor pressure vessels in service. In 1975, a report was prepared concerning the interpretation of the intermediate vessel test results obtained to that date with respect to the safety of actual vessels. It was concluded that only inadequate material properties, large flaws or extreme loading conditions exceeding the values permitted by present codes remain as possible causes of vessel malperformance under operating conditions.⁵⁷ Pressurized thermal-shock transients fall in the latter category, and are presently the subject of intensive investigation (see Task H.10).

The HSST Program staff also participated actively in the work of a recent NRC task group which prepared recommended analysis procedures for determining the safety margins of vessels containing low upper shelf toughness materials.⁵⁸ A follow-up report containing comparative example calculations by some of the methods discussed was also presented to the ASME Section XI Working Group on Flaw Evaluation and subsequently published as a NUREG report.⁵⁹ The data from intermediate test vessel V-8A relate directly to this subject,³⁷ and their posttest analysis will provide an opportunity to evaluate the proposed criteria.

2.3 Plan of Action

The plan of action for each subtask is depicted in the milestone chart for Task H.2. A transition from previous accomplishments to the planned activities is provided in many instances by the background discussions given in Section 2.2 above.

2.3.1 Fracture-Toughness Determinations and Strength Methods

The emphasis continues to be on providing analytical models for representing the behavior of finite-length flaws in RPV steels under overcooling accident conditions. Predictions of the initiation, propagation, and arrest of flaws are involved for materials whose fracture characteristics vary in position and time. Consequently the applicability of concepts for a unified fracture mechanics strength methodology to treat different regions of fracture behavior will be developed and/or assessed. In the near term, these efforts will be augmented by the issuance of a report on small specimen fracture toughness in the cleavage range and a report on the cleavage to fibrous transition. Under the current budgetary plan, the level of effort on the unified theory is modest during FY 1984, with a more vigorous effort in FY 1985 when the predictions of candidate theories will be evaluated against available data from pressurized thermal-shock tests and wide-plate crack arrest tests.

In concert with improved fracture modeling, compatible bases for stress analysis (constitutive equations) are required. Time (rate) dependent inelastic material response will be considered in terms of constitutive equations that do and those that do not distinguish between plastic and creep strains. The applicability of current theories of viscoplasticity will be assessed first in terms of dynamic analyses of fast-running cracks and of arrest events. The laboratory tests that are required to identify and quantify properties that appear in these equations must be performed as a part of implementing the assessments for the specific materials of interest. Assessments of the applicability of constitutive equations must include an evaluation of the following aspects: (a) the ability to predict the deformation (rate-dependent) response of laboratory specimens, (b) the ability to predict the response of structural configurations that include multiaxial stresses and stress gradients, (c) compatibility with practicable analysis tools such as finite-element computer programs, and (d) compatibility of mechanical properties requirements with existing data bases or those that might be developed with reasonable cost. Milestone H.2.1.E as defined in this plan is (through a subcontract) to employ a selected theory of viscoplasticity in an advanced version of the dynamic fracture analysis computer code FRACTDYN. A combined ORNL and subcontractor approach is envisaged over the longer run if the initial studies show sufficient promise. After current theories of viscoplasticity are assessed, further analysis methods developments would be pursued as needed.

In addition to investigating the application of advanced rate-dependent inelastic constitutive equations to fracture mechanics analysis, the effects of the conversion of plastic work to heat near the tip of a running crack will be investigated. Since the zone of actual material separation is very near the crack tip, this energy conversion may affect the temperature at the point of incipient microcracking, and this affects the toughness itself. The interaction of this effect with the effects of strain rate will be examined with a view toward making estimates of the crack-arrest toughness when direct measurements cannot be made.

2.3.2 Analysis Methods and Computer Programs

An emphasis in this subtask continues to be on analytical techniques applicable to the analysis of the behavior of finite-length flaws under OCA conditions. A second emphasis is on the provision of dynamic fracture analysis programs that are compatible with available fracture theories and constitutive equations. In addition to computer based methods, direct analysis methods are developed where possible for classes of problems.

The upper-shelf analysis capability that is presently in the computer code OCA/USA will continue to be improved, including an extension to be applicable to clad vessels. A report will be prepared in FY 1984 by the University of Maryland covering the developing and qualification of the dynamic fracture analysis program SAMCR. This program is considered to provide a backup or confirmatory dynamic analysis capability to other programs, e.g., FRACTDYN. A dynamic crack analysis capability will be incorporated into the ADINA-ORVIRT system to give ORNL an in-house dynamic analysis capability. This will also serve as the basis for a later incorporation of improved unified fracture models and viscoplastic constitutive equations into the ADINA-ORVIRT system. Considering the current overall capabilities of ADINA, current viscoplasticity theories can be exercised in this finite-element analysis program with relatively low developmental requirements when compared with other large computer codes.

As noted in the background discussions, a ligament instability analysis has been developed for an externally flawed vessel. This method is based on direct analysis approaches and not on finite-element or other numerical techniques. An analogous ligament instability analysis will be developed for an internally flawed vessel. Although the theoretical foundations are the same for the two situations, an internally flawed vessel is the specific geometry of concern in overcooling accident situations.

2.3.3 Analyses of Specific Configurations

This Subtask (H.2.3) augments Subtask H.2.2 by further qualifying fracture analysis capabilities through the analysis of chosen configurations. Milestone H.2.3.A is aimed at furthering the understanding of warm prestressing (WPS) through the elastic-plastic analysis of sample structures. Since beams have been used in some of the landmark experiments to demonstrate WPS, beams will be chosen for analyses. Classical theories of plasticity, such as isotropic hardening, kinematic hardening, and combined isotropic-kinematic hardening models, will be used with the ADINA computer programs to look at history effects on the stress field in the vicinity of a crack. Since versions of such plasticity models are now in ADINA, it offers a possible tool for this study. Of course, associated extensions would need to be made to ORVIRT and values for the elastic-plastic properties appropriate to the materials of interest must be inserted into the program.

2.3.4 Guidelines for Codes and Standards

The plan of action here includes a continuation of contributions of fracture toughness and strength results and data from the program to the goals of relevant technical committees. These committees include the PVRC/MPC Task Group on Reference Toughness, ASTM Committee E-24 on Fracture Toughness Testing, and the ASME BPV Code, Section XI Working Group on Flaw Evaluation. The results are also to be made available to US-NRC Regulatory Guide development and to US-NRC position papers on the resolution of safety issues. Specific issues that are active at this time are identified in the Background Section 2.2.4 above.

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2.5 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.1 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.2 FRACTURE METHODOLOGY AND ANALYSIS

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
H.2.1 <u>Fracture Toughness Determinations and Strength Methods</u>																									
A. Issue Report on Small Specimen Fracture Toughness in Cleavage Range		a		b																					
a. Complete assessment of size effects on existing data		▼																							
b. Complete assessment of micro-cracking and physical factors involved				▼																					
B. Issue Summary Report on Cleavage-Fibrous Fracture Investigations (University of Maryland)				a																					
a. Complete studies for A533B steel				▼																					
b. Complete studies and comparisons for A508 and two other steels																									
C. Complete Testing and Issue Report on PCCV Round Robin																									
D. Issue Report on Concepts of a Unified LEFM-EPFM Methodology for use with Visco-Plastic Analysis of Fracture (H.2.1.E)																									
a. Identify and screen candidate concepts																									
b. Evaluate concepts against practicable requirements for application																									

MILESTONE STATMENT AND SCHEDULE

Task: H.2 FRACTURE METHODOLOGY AND ANALYSIS (continued)

SUBTASK/MILESTONE	FY 83				FY 1984								FY 85				FY 86	FY 87	Beyond FY 87						
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4	86	87			
D. Issue Report on Concepts of a Unified LEFM-EPFM Methodology for use with Visco-Plastic Analysis of Fracture (continued)																									
c. Evaluate concepts against available data, e.g., plate, and PTSE data																									
E. Issue Report on Assessing Current Visco-Plastic Constitutive Equations for Analysis of Fast Running Cracks in RPV Steels																									
a. Select an initial candidate constitutive model																									
b. Complete quantification of model parameters on basis of available RPV steel data																									
c. Incorporate constitutive equations in state-of-the-art dynamic computer code																									
d. Complete analyses of benchmark problems and first two series of wide-plate tests and draft report (see H.5.1.B & H.5.1.C)																									
F. Complete Development of Improved Visco-Plasticity Equations and Techniques for Application as Needed																									

MILESTONE STATEMENT AND SCHEDULE

Task: H.2 FRACTURE METHODOLOGY AND ANALYSIS (continued)

SUBTASK/MILESTONE	FY 83				FY 1984									FY 85				FY 86	FY 87	Beyond FY 87				
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
H.2.2 Analysis Methods and Computer Programs																								
A. Complete Development of ORVIRT-3D Nonlinear Analysis	▲																							
B. Complete ORMGEN-3D Mesh Generation Program	▲																							
C. Issue Report on Development of Finite-Element Code .MCR for Dynamic Fracture Analysis (University of Maryland)										▲														
D. Complete Development of Analytical Tools Capable of Predicting Finite-Length Flaw Behavior	a ▼		b, c ▼																d ▼			▲		
a. Develop ADINA-ORVIRT analysis for combined pressure and thermal loadings of cylinders with finite-length flaws with and without cladding	▼																							
b. Develop influence coefficients for finite-length flaws and for use in OCA-USA			▼																					
c. Develop interpretations of finite length flaw definition for PTSE applications			▼																					
d. Develop OCA-USA to be applicable to clad vessels																				▼				

MILESTONE STATEMENT AND SCHEDULE

Task: H.2 FRACTURE METHODOLOGY AND ANALYSIS (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87				
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4							
E. Complete Development of Analytical Tools Capable of Predicting Inelastic Fracture Behavior of 2-D and/or 3-D Structures (ORNL)			a	b																							
a. Develop OCA-USA computer code (with upper-shelf arrest analysis) for use in PTSE-1																											
b. Develop ligament instability analysis for PTSE-1 and incorporate into OCA-USA code																											
c. Incorporate dynamic crack model into ORNL analysis system based on state-of-the-art techniques																											
d. Incorporate visco-plastic constitutive equations and unified fracture model into ORNL fracture analysis system																											
F. Complete Development of Ligament Instability Analysis for Internally Flawed Vessel																											
H.2.3 <u>Analyses of Specific Configurations</u>																											
A. Complete Interpretive Study of Warm Prestressing Phenomena through Analyses of Sample Structures																											
a. Perform classical elastic-plastic analyses of sample scenarios																											

MILESTONE STATEMENT AND SCHEDULE

Task: H.2 FRACTURE METHODOLOGY AND ANALYSIS (continued)

SUBTASK/MILESTONE	FY 83				FY 1984								FY 85				FY 86	FY 87	Beyond FY 87			
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S				1	2	3
A. Complete Interpretive Study of Warm Prestressing Phenomena through Analyses of Sample Structures (continued)																						
b. Perform visco-plastic analyses of sample scenarios																						▽
B. Complete Analyses of HRD Beltline Crack Behavior Test																						△
H.2.4 Guidelines for Codes and Standards																						
A. Maintain Membership in PVRC/MPC Task Group on Reference Toughness																						→
B. Maintain Membership on ASTM Committee E-24 on Fracture Toughness Testing																						→
C. Maintain Membership on ASME BPV Code Section XI Working Group on Flaw Evaluation				▼ ^a																		→
a. Issue report on methods for analyzing ductile flaw stability				▼																		→
D. Provide Program Results to NRC Regulatory Guides and Position Papers				▼ ^a																		→
a. Complete contribution to report on resolution of Task A-11 Materials Toughness Safety Issue				▼																		→

3. HSST TASK H.3 MATERIAL CHARACTERIZATION AND PROPERTIES

3.1 Objective

The primary objective of this task is to characterize the mechanical and physical properties, with emphasis on fracture behavior, of the materials used in the structural experiments which are carried out under other tasks of the HSST Program. The materials currently include those from intermediate test vessels, thermal-shock cylinders, pressurized thermal-shock vessels, wide-plate crack-arrest plates, and clad beams. Other supporting objectives include the development of test methods, active participation in codes and standards activities, and the use and development of metallurgical tools to support all the activities.

3.2 Background

The general activities assigned to this task have been an integral part of the HSST Program since its inception. The activities performed are fairly broad in terms of mechanical and physical metallurgy and are primarily directed to the support of the structural testing tasks of the HSST Program. Prior to FY 1984 the activities have been treated as parts of the other tasks. Now, however, a distinct task has been established to provide more visibility to the area of materials characterization and to enhance planning and management within ORNL.

The task is carried out according to the work breakdown structure shown in Fig. 3.1. Activities include the microstructural examination of commercial heavy-section steel plates, forgings and weldments, mechanical testing with emphasis on fracture properties, heat treatment studies to produce desired properties for structural tests, welding fabrication, posttest analysis of fracture surfaces using scanning electron fractography, and development of test methods and analytical methods.

Activities recently undertaken include the development of a crack arrest testing facility, participation in the ASTM round robin on crack arrest, and participation in the HSST-sponsored international round robin on dynamic precracked Charpy testing.

Major accomplishments arising from this task include:

1. Development of tempering treatment procedures for achieving desired material fracture toughness values for vessel and other structural tests.
2. Demonstration of large scatter in transition region fracture toughness and need for lower-bound analysis.
3. Demonstration of size-effects relationship in fracture toughness testing.
4. Development of correlation between onset of Charpy upper-shelf and 100% ductile fracture using a load-drop technique in an instrumented impact test.

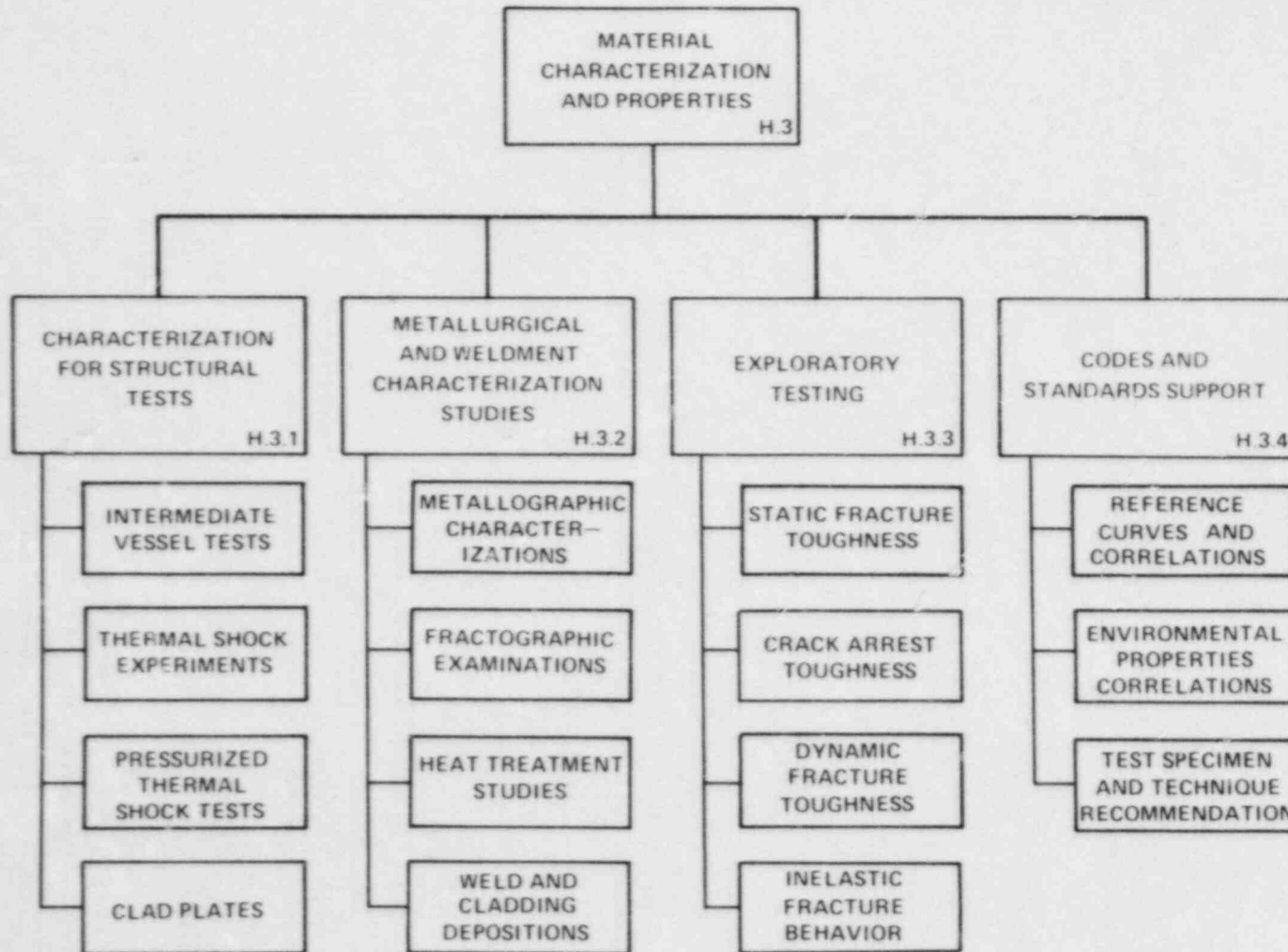


Fig. 3.1 Work breakdown structure for the HSST Task H.3 Material Characterization and Properties.

3.3 Plan of Action

3.3.1 Characterization for Structural Tests

Detailed examination and measurements of the ITV-8A fracture surface have been completed. Additional posttest verification fracture toughness specimens will be tested to obtain J-R curves at 150°C, the vessel test temperature. Posttest characterization testing for TSE-7 is under way and includes Charpy V-notch (C_v) and fracture toughness (K_J) tests with material removed from the test vessel for comparison with the vessel test results. This testing will be completed in the first half of FY 1984.

Pretest characterization has been completed for PTSE-1 as have the tempering studies that provided the heat treatment schedule for the vessel. Following the conduct of PTSE-1, posttest verification fracture toughness (K_J) and C_v tests will be performed by the end of FY 1984. The test plan for the low upper-shelf weld to be used in PTSE-2 and TSE-8 will be similar to those used for previous thermal-shock tests. Mechanical properties will be determined prior to the vessel being heat treated to verify the tempering temperature. Posttest characterization will also follow previous plans with completion scheduled for early FY 1986. In addition to the tensile, C_v and K_J tests, crack arrest tests will also be conducted to determine K_{Ia} for all the upcoming thermal-shock and pressurized thermal-shock experiments.

PTSE-3 and TSE-9 involve additional characterization because they will be tests with stainless steel clad vessels. In addition to the usual test plan, mechanical properties will be determined for the stainless steel weld metal cladding. Because the cladding is relatively thin (4 to 6 mm), subsize specimens will be required. Development of test specimens and procedures is continuing in preparation for the characterization of the thermal-shock and pressurized thermal-shock experiments as well as for the clad plate tests. The pretest investigations will be completed for TSE-9 by the end of FY 1985 and for PTSE-3 early in FY 1986.

Characterization testing for the clad-plate tests is similar to that for the clad vessels except that tests will be performed for the ORNL-fabricated single-wire submerged-arc cladding as well as three-wire series-arc cladding fabricated by Combustion Engineering (CE), Chattanooga. Both of those projects include the use of weld metal cladding in sufficient thickness to facilitate the removal of standard C_v , tensile, and 0.5T compact specimens for correlation with subsize specimens. Subsize-specimen testing will also be performed with clad nozzle drop-outs procured from CE; this work will be done in FY 1985. Efforts will be continued to obtain drop-outs from other manufacturers.

The testing required for the wide-plate crack arrest tests is not well defined at this time, but it is expected to involve the full range of mechanical property tests, including conventional crack arrest tests. Complementary development of an alternate crack arrest test specimen and procedures are under way and will continue in support of all the structural tests with particular emphasis on the needs of the wide-plate crack arrest program.

3.3.2 Metallurgical and Weldment Characterization Studies

The activities under this subtask are conducted in parallel with those for the previous subtask. Metallurgical studies involve the use of metallography to examine the microstructure of the materials used for structural tests. Fractography studies involve precision measurements of fracture surfaces and the use of scanning electron microscopy to correlate material deformation behavior with test observations. When necessary, other metallographic tools such as transmission electron microscopy will be used to provide a more detailed examination of microstructural features. This type of investigation is particularly helpful with materials new to the program, such as cladding.

3.3.3 Exploratory Testing

The activities of this subtask are related to the needs of the structural testing tasks, but they are better described as separate research and development. The plans and schedules are not well defined because most of those activities are not separately funded and the path of development builds upon previous results. In general, they are performed as time and resources permit.

The alternate crack arrest specimen development is performed in parallel with the development of in-house standard crack-arrest testing capabilities and participation in the ASTM round robin. Exploratory investigations in the area of experimental fracture mechanics include the continued refinement of compliance-type J-R testing procedures, development of a potential-drop system for crack growth monitoring, and fractographic studies and statistical analyses to understand the lower-bound fracture toughness problem. The development of remote crack-arrest testing procedures is directly related to Subtask H.6.5 of the irradiated crack arrest program. The development of remote testing procedures will be used for hot cell testing of irradiated specimens and is scheduled for completion by the end of FY 1985. The testing of dynamic instrumented precracked Charpy (PCC_V) specimens is virtually completed and provides the ORNL in-house contribution to the international round robin testing program initiated by the HSST Program in 1981 (see Milestone H.2.1.C). This round-robin program is an attempt to understand the relationship between dynamic PCC_V fracture toughness results with those obtained from more conventional compact specimen tests and, of course, the results from actual vessel tests. The material was obtained from thermal-shock cylinder 2 (TSC-2) used for TSE-5A.

3.3.4 Codes and Standards Support

Various staff members actively participate in codes and standards organizations such as the American Society for Testing and Materials (ASTM), American Society of Mechanical Engineers (ASME), Pressure Vessel Research Committee (PVRC), and Metals Properties Council (MPC). Participation on various committees of those organizations provides one important forum for transfer of technology gained from HSST Program activities as well as the opportunity to gain feedback from user organizations and other research organizations. It also provides a means for

the staff to stay current on codes and standards developments. These activities are performed on a continuing basis and are anticipated to remain active during the life of the HSST Program.

3.4 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.3 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.3 MATERIAL CHARACTERIZATION AND PROPERTIES

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85			FY 86	FY 87	Beyond FY 87			
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
H.3.1 <u>Characterization for Structural Tests</u>																									
A. Complete Characterization Testing and Analysis for ITV-8A		a	b				△																		
a. Complete detailed examination and measurements of fracture surface		▼																							
b. Complete posttest tensile and initiation toughness testing			▼																						
B. Complete Characterization Testing and Analysis for ITV-10																									△
C. Complete Characterization Testing and Analysis for TSE-7		a	b				c	d																	
a. Complete tempering studies for vessel heat treatment schedule		▼																							
b. Complete pretest mechanical property and fracture toughness tests		▼																							
c. Complete posttest mechanical property and fracture toughness tests							▼																		
d. Complete analysis and interpretation of laboratory tests																▼									

MILESTONE STATEMENT AND SCHEDULE

Task: H.3 MATERIAL CHARACTERIZATION AND PROPERTIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87			
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4						
D. Complete Characterization Testing and Analysis for PTSE-1		▼ ^a																								
a. Complete tempering studies for vessel heat treatment schedule		▼																								
b. Complete posttest mechanical property and fracture toughness tests													▼													
c. Complete analysis and interpretation of laboratory data															▼											
E. Complete Characterization Testing and Analysis for PTSE-2 and TSE-8																	▼ ^a			▼ ^b	▼ ^c	▲				
a. Complete pretest mechanical property and fracture toughness tests (including K_{Ia} for ITV-8A material)																	▼									
b. Complete posttest mechanical property and fracture toughness tests																				▼						
c. Complete analysis and interpretation of laboratory tests																					▼					
F. Complete Characterization Testing and Analysis for TSE-9																					▼ ^a	▼ ^b	▼ ^c	▼ ^d	▲	
a. Complete pretest mechanical property and fracture toughness tests - base metal																					▼					

MILESTONE STATMENT AND SCHEDULE

Task: H.3 MATERIAL CHARACTERIZATION AND PROPERTIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
F. Complete Characterization Testing and Analysis for TSE-9 (continued)																									
b. Complete pretest mechanical property tests with clad specimens																									
c. Complete posttest mechanical property and fracture toughness tests																									
d. Complete analysis and interpretation of laboratory data																									
G. Complete Characterization Testing and Analysis for PTSE-3																									
a. Complete pretest mechanical property and fracture toughness tests of base metal and clad specimens																									
b. Complete posttest mechanical property and fracture toughness tests																									
c. Complete analysis and interpretation of laboratory tests																									
H. Complete Characterization Testing and Analysis for Clad-Plate Tests																									
a. Complete mechanical property and fracture toughness tests for one-wire clad plates																									

Task: H.3 MATERIAL CHARACTERIZATION AND PROPERTIES (continued)		MILESTONE STATEMENT AND SCHEDULE																															
		FY 83				FY 1984				FY 85				FY 86				FY 87				Beyond FY 87											
		1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
SUBTASK/MILESTONE																																	
I. Complete Characterization Testing and Analysis for Wide-Plate Crack Arrest Specimens (continued)																																	
c. Complete studies of A533B steel heat treated to simulate PTSE-1 material																																	
J. Complete Characterization as Needed for ASTM Round Robin on Crack Arrest																																	
H.3.2 Metallurgical and Weldment Characterization Studies																																	
A. Complete Metallographic and Fractographic Characterizations of Test Vessel Materials																																	
a. Fractography for ITV-8A																																	
b. Metallography and fractography for TSE-7																																	
c. Fractography for PTSE-1																																	
d. Metallography and fractography for TSE-8																																	
e. Metallography and fractography for PTSE-2																																	
f. Metallography and fractography for PTSE-3																																	

MILESTONE STATEMENT AND SCHEDULE

Task: H.3 MATERIAL CHARACTERIZATION AND PROPERTIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4	86	87			
B. Complete Heat Treatment Studies	a	b																				c			
a. Tempering study for TSE-7	▼																								
b. Tempering study for PTSE-1	▼																								
c. Tempering study for wide-plate specimens (see H.3.1.1.c)																						▼			
C. Complete Characterization of Weld and Cladding Depositions			a																			b	c	d	
a. Metallography and fractography for one-wire clad plates			▼																						
b. Metallography and fractography for phase 1 three-wire clad plates																						▼			
c. Metallography for commercial three-wire archival cladding																							▼		
d. Metallography and fractography for phase 2 three-wire clad plates																							▼		
H.3.3 <u>Exploratory Testing</u>																									
A. Complete Initial Development and Construction of Alternate Crack-Arrest Specimen Test Facility																								▲	
B. Complete Testing, Analysis, and Data Interpretation for Dynamic PCC Round Robin (see H.2.1.C)																									▲

MILESTONE STATEMENT AND SCHEDULE

Task: H.3 MATERIAL CHARACTERIZATION AND PROPERTIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984									FY 85				FY 86	FY 87	Beyond FY 87			
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4			
C. Complete Development of Crack-Arrest Test Capabilities		▼ ^a									▼ ^b									▼ ^{c,d}			▲
a. Develop standard crack-arrest testing capability at ORNL		▼																					
b. Complete ORNL testing in ASTM round robin					—	—	—	—	—	—	▼												
c. Complete development of initial alternate crack-arrest test method				—	—	—	—	—	—	—	—	—	—	—	—	—				▼			
d. Complete development of remote crack arrest specimen and test procedure (see H.6.5.C.a)																	—	—	—	▼			
D. Conduct Exploratory Investigations in Area of Experimental Fracture Mechanics to Include Metallurgical Interactions (continuing)																							▲
H.3.4. <u>Codes and Standards Support</u>																							▲
A. Advise Standards and Codes Organizations Relative to Changes or Additions Recommended for Reference Curves and Correlations (continuing)																							▲
B. Advise Standards and Codes Organizations Relative to Changes or Additions Recommended for Test Methods (continuing)																							▲

4. HSST TASK H.4 ENVIRONMENTALLY ASSISTED CRACK GROWTH TECHNOLOGY

4.1 Objective

The objective of Task H.4 is to characterize the crack growth rate properties of light-water reactor vessel materials exposed to primary coolant environment, and to provide improved data correlations as appropriate to design codes and regulatory guides.

4.2 Background

In assessing the integrity of nuclear components, the possible presence of cracks or defects is an important consideration. There are two things which can cause cracks to propagate in structures, and both must be considered in design assessments. The first is severe loadings which can cause single or multiple crack jumps, and the second is fatigue loadings, which result from normal plant operation as well as operational transients, and can cause progressive extension of cracks. While the single loadings are essential to consider, the net risk to the structure from these is relatively low, because the high-probability events are low in severity, while the severe events are very low probability. The fatigue loadings result in the highest net risk to the propagation of a flaw in a structure, because they are virtually certain to occur.

This fact was recognized in the early stages of the Heavy-Section Steel Technology Program, and an experimental program was developed to characterize the fatigue crack growth of pressure vessel steels in light-water reactor environments in the late sixties. It was also recognized in the development of flaw evaluation criteria in Section XI of the ASME Code, where fatigue crack growth is one of the key considerations.

This program provided the first verification of Kondo's discovery in 1971 that low-frequency loadings in water environments result in significant acceleration in crack growth rates above those for air environments.¹ The data produced by this program provided the basis for the early incorporation of water-environment effects on crack growth in the ASME Code, in the 1974 edition of Section XI Appendix A.² This was the first incorporation of environmental effects on crack growth in a code or standard in the world.

The program continued, with emphasis in the mid-seventies being directed at the effects of environment on plates, forgings, welds, and heat-affected zones, to determine if all behaved similarly. The findings were that they all behaved similarly, but more complete studies revealed that the crack growth rate did not increase in a linear fashion on a logarithmic plot, as with inert environments, but tended to flatten out at a growth rate which was dependent on the frequency of loading. A significant effect of R ratio was also discovered, and verified by other investigators. Again the data produced in this program formed the majority of the data base used to develop a revision to the ASME Code reference crack growth curves for water environment, which was accomplished in the Winter addendum to the 1980 Code.³

Most recent work has resulted in the discovery that the degree of environmental enhancement for pressure vessel steels can be different for different heats of the same steel. It was found that the sulfur content of the steel was the key factor, with high-sulfur levels resulting in significant enhancement, while low-sulfur steels showed only slight enhancement over growth rates observed in air.⁴ This was a significant finding, because it shows that the newer, low-sulfur steels used in recent construction will be less susceptible to environmental fatigue.

Another recent discovery of this task was that cracks in pressure vessel steels can grow under constant load in water environments, under certain conditions.⁵ The relationship between this mode of subcritical crack growth and fatigue is currently under investigation, and efforts are also being aimed at better defining the conditions under which this growth can occur.

The program is continuing with emphasis now being placed on further understanding the mechanisms involved in the process of environmental enhancement of fatigue crack growth. This understanding is essential to enable accurate predictions of crack growth during service, because it is impossible to model all the types of loadings which can occur. The overall goal remains to develop accurate characterization of subcritical crack growth for use in the assessment of defects found in operating plants.

4.3 Plan of Action

This task continues to be carried out through subcontract with Westinghouse Electric Corporation, Nuclear Technology Division. The work breakdown structure is shown in Fig. 4.1. The first priority continues to be to complete the characterization of the two major known influences on the enhancement of crack growth rates in water environments. These are the influences of the material itself through sulfur content [H.4.1], and the influence of the water environment [H.4.1]. Both of these tasks are now underway.

Another important task is developing a relationship between cyclic-fatigue and static-load crack growth [H.4.2]. This work is interrelated with the mechanisms of environmental enhancement of crack growth, and should lead to considerable improvement in understanding in this area. The key to the ultimate goal of the program is to predict accurately the environmental enhancement of crack growth.

The extension of the characterization studies to piping steels is another key task where the similarities and differences between pressure vessel and piping steels will be investigated [H.4.2]. This must be done to decide whether the present ASME Code reference fatigue crack growth curves are applicable to piping steels. If they are not applicable, a suitable replacement must be developed.

The interrelationships between loading frequency and applied R ratio have been characterized generally by the tests which have already been completed, but a series of key experiments are needed to complete the characterization. These experiments are needed to define the threshold limits of R ratio and frequency effects, which have not yet

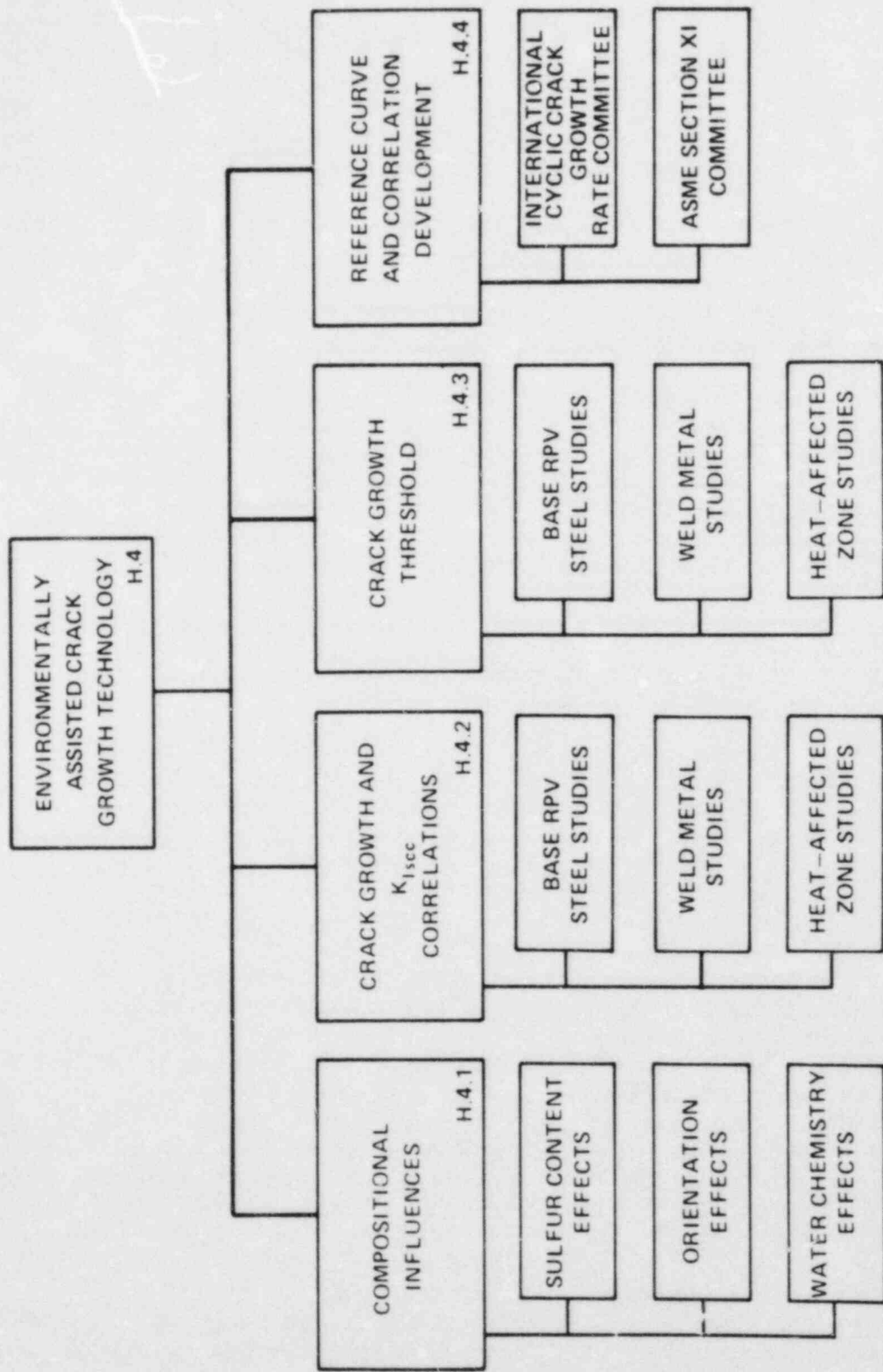


Fig. 4.1 Work breakdown structure for HSST Task H.R Environmentally Assisted Crack Growth Technology.

been developed. In particular, R ratios greater than 0.75 have seldom (if ever) been attempted in corrosion fatigue testing, and data at frequencies lower than one cycle per minute are very sparse [H.4.3].

The ultimate goal and culmination of the task will be the proposal of revisions to the ASME Code reference crack growth curves for environmental crack growth. Involved with this task is the experimental verification of crack growth predictive methodology through selected model tests. Also under this task is continued participation in the International Cyclic Crack Growth Rate Group, to enable research in this field being performed around the world to be incorporated into any revision of the reference curves.

4.4 References

1. T. R. Mager, D. M. Moon, and J. D. Landes, "Fatigue Crack Growth Characteristics of A533 Grade B Class 1 Plate in an Environment of High-Temperature Primary Grade Nuclear Reactor Water," *Trans. ASME J. Pressure Vessel Technol.*, (November 1976).
2. T. U. Marston (ed.), *Flaw Evaluation Procedures: ASME Section XI*, EPRI Report 719-SR, August 1978.
3. W. H. Bamford, "Technical Basis for Revised Reference Crack Growth Rate Curves for Pressure Boundary Steels in LWR Environment," *Trans. ASME, J. Pressure Vessel Technol.*, 102 (November 1980).
4. W. H. Bamford, "Environmental Cracking of Pressure Boundary Materials, and the Importance of Metallurgical Considerations," in *Aspects of Fracture Mechanics in Pressure Vessels and Piping*, PVP-58, ASME 1982.
5. W. H. Bamford, D. M. Moon, and L. J. Ceschini, "Studies of Statistically and Dynamically Loaded Cracks in Pressurized Water Environment," presented at *Corrosion 83*, Anaheim, California, April 1983, to be published in *Corrosion*.

4.5 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.4 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.4 ENVIRONMENTALLY ASSISTED CRACK GROWTH TECHNOLOGY

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
H.4.1 Compositional Influences																									
A. Complete Study of Plate-Orientation Effects on Cyclic Crack Growth Rates for A533B Steel				▲																					
B. Complete Study of Sulfur Effects on Crack Growth Rates in A533B Steel				▼																					
a. Complete study of high-sulfur plates				▼																					
b. Complete study of low-sulfur plates																									
C. Complete Study of Boron Effects																									
D. Complete Installation of Electro-Chemical Potential Measurement Systems on Fatigue Chambers to Continuously Monitor Water Environment																									
H.4.2 Crack Growth and K_{Isc} Correlations																									
A. Complete Tests to Correlate K_{Isc} and Cyclic Crack Growth																									
a. Complete tests on two heats of A533B steel																									
b. Complete tests on weld metal and heat-affected zone materials																									
c. Complete tests of two additional heats																									

MILESTONE STATEMENT AND SCHEDULE

Task: H.4 ENVIRONMENTALLY ASSISTED CRACK GROWTH TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984									FY 85				FY 86	FY 87	Beyond FY 87								
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1				2	3	4					
A. Complete Tests to Correlate K_{Isc} and Cyclic Crack Growth (continued)																												
d. Complete constant extension rate tests (CERT) for the additional tests																												
e. Issue report on available K_{Isc} vs. fatigue data																												
B. Complete Tests for Three Heats of Piping and Structural Steels																												
a. Complete CERT tests																												
b. Complete cyclic crack growth tests																												
c. Complete comparison of results with RPV steel data																												
H.4.3 Crack Growth Threshold																												
A. Issue Report on High R Ratio ($R \geq 0.7$) Crack Growth Studies																												
a. Complete tests																												
b. Complete saturation assessments																												
B. Issue Report on Low-Frequency Crack Growth Studies																												
a. Complete tests																												
b. Complete tests and threshold assessments																												

5. HSST TASK H.5 CRACK ARREST TECHNOLOGY

5.1 Objective

The objective of Task H.5 is to provide crack arrest test data over ranges of temperature and materials to support validation of structural assessment methods, to define structural tests, to validate ASTM test procedures, and to develop procedures for remote testing.

5.2 Background

Example calculations for a reference calculational model vessel containing a long axial crack and subjected to pressurized thermal-shock (PTS) loading show that high levels of crack arrest toughness, at temperatures approaching the upper shelf, are needed to ensure vessel safety.¹ In addition, calculations for a planned intermediate vessel PTS test show that crack-arrest values higher than previously measured with compact specimens are required for predicting the test results.² Few crack-arrest toughness measurements have been made above $175 \text{ MPa}\sqrt{\text{m}}$, but some have been made by Japanese investigators using edge cracked wide-plate (ESSO) specimens.^{3,4} Tests of a similar nature are being planned using HSST program materials, and an analysis procedure based on the FRACTDYN computer code is being developed. The analysis procedure will be applied to selected existing Japanese data in order to plan the location of instruments for the HSST tests, and to the HSST results to determine crack arrest toughness values and a versus K relations.

The current procedure for making crack arrest toughness measurements is based on the use of a transverse wedge loaded rectangular compact specimen. A disadvantage of this specimen is that K_I decreases with a/W , forcing the use of high values of K for initiation, with attendant large plastic zones, in order to obtain only moderately high values of K_{Ia} for sufficiently long crack jumps. Despite lubrication, friction effects between the bottom surface of the specimen and the supporting base complicate the interpretation of data. Inverted wedge cones or partial shims may remedy this problem, but they may also eliminate a compensating phenomenon, which is the delayed release of strain energy stored near the split pins that might otherwise cause displacement oscillations and reinitiation after arrest. These phenomena require further investigation.

5.3 Plan of Action

The plan of action is described below in terms of the three major subtasks that comprise Task H.5. The associated work breakdown structure is shown in Fig. 5.1.

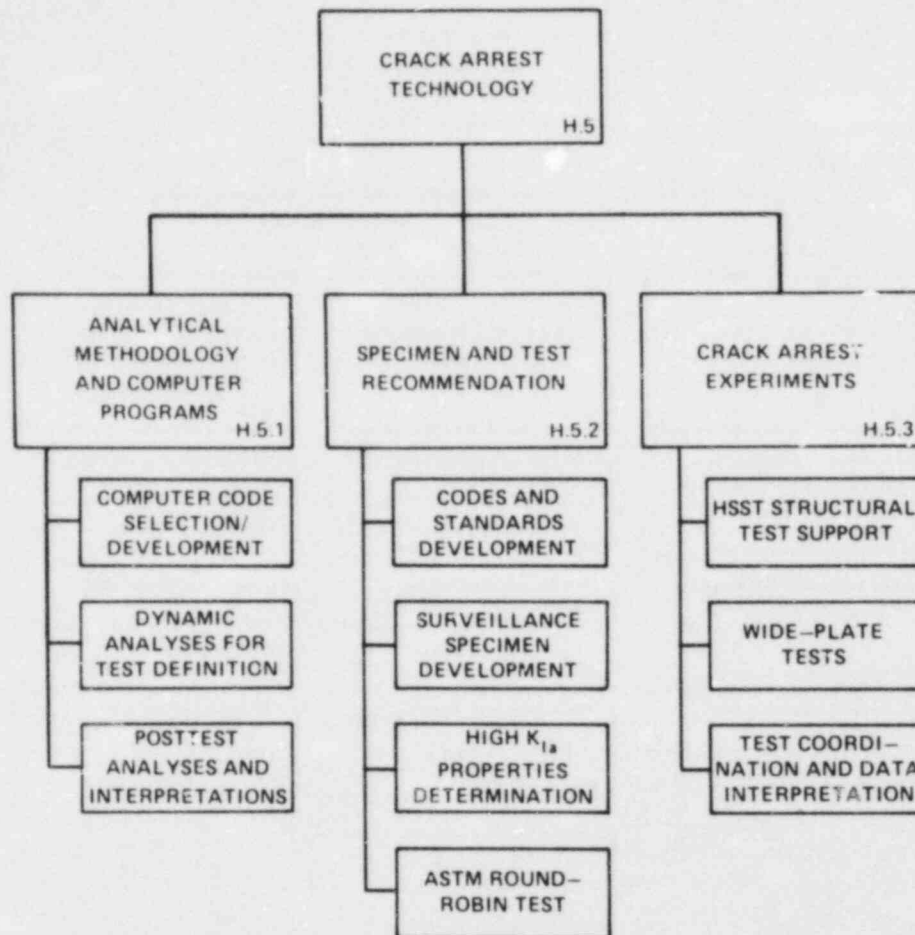


Fig. 5.1 Work breakdown structure for HSST Task H.5 Crack Arrest Technology.

5.3.1 Subtask H.5.1 Analytical Methodology and Computer Programs

The emphasis in this subtask is on analyzing the crack arrest experiments performed in Subtask H.5.3. This is accomplished in concert with computer program development efforts in Task H.2. The planned efforts are aimed mostly at wide-plate tests covering three RPV materials. Pretest analyses are to be performed for test definition. Results from posttest analyses are to be compared with test results to either validate or improve analysis methods. The pretest analyses for the first series of wide-plate crack arrest tests are to use state-of-the-art dynamic analyses. Later analyses may use more advanced theoretical bases, if warranted by the results of Subtask H.2.1, such as viscoplasticity.

5.3.2 Subtask H.5.2 Standardized Specimen and Test Recommendation

Much of the activity in this subtask is being carried out under subcontract with the University of Maryland. One important goal is the development of an ASTM standard on crack arrest testing. The international round-robin testing will be coordinated, including test material distribution, data interpretation, and evaluation of the draft standard, under this subtask.

Geometric modifications to the CT specimen may help to eliminate or alleviate the decrease of K_I with a/W . These include variable depth side grooves and a reverse tapered profile. Other specimen designs to be investigated include a lever or "nut cracker" specimen, and a slotted pressurized cone.

5.3.3 Subtask H.5.3 Crack Arrest Experiments

This subtask has two emphases. The first relates to the generation of small-specimen crack-arrest data in support of structural tests and analyses. Four materials are currently under investigation: low upper-shelf weld from ITV-8A, A508 steel from TSE-7, steel from PTSE-1, and A533B steel from the wide plates to be studied in this subtask and discussed below. After these are completed, data will be generated on low upper-shelf weldment in support of PTSE-2, TSE-8, and second series of wide-plate tests. This will then be followed by tests on the base material to be used in PTSE-3. Much of this K_{Ia} testing is performed at Battelle Columbus Laboratories under subcontract, and a computerized K_{Ia} data base is also maintained at BCL for publicly held data.

The second emphasis is to perform three series (six tests each) of crack arrest tests on wide-plate specimens (approximately 1m x 1m x .1m) under tensile load and a transverse temperature gradient. The goal is to measure crack-arrest toughness near or under upper-shelf conditions and with the crack propagating into a rising K_I field. The three test materials are quenched and tempered A533B steel, low upper-shelf weldment, and A533B that has been heat treated to simulate the material used in the first pressurized thermal-shock experiment (PTSE-1). In order to be compatible with the budget assumptions used in this plan, the tests for the first material are scheduled to be performed in FY 1984, the second material is to be tested in FY 1985, and the six tests for the third material scheduled for FY 1986. The testing effort will be performed under subcontract with an organization to be selected in early FY 1984, and which must have equipment capable of applying the required loads (up to about six million pounds).

5.4 References

1. A. Sauter, R. D. Cheverton, and S. K. Iskander, *Modification of CCA-1 for Application to a Reactor Pressure Vessel with Cladding on the Inner Surface*, ORNL/TM-8649, Oak Ridge National Laboratory.

2. R. H. Bryan, "Pressure Vessel Investigations," pp. 78-132 in *Heavy-Section Steel Technology Program Quart. Prog. Rep. for October-December 1982*, ORNL/TM-8369/V4, Oak Ridge National Laboratory.
3. Y. Nakano, "Stress Intensity Factor During Brittle Crack Propagation and Arrest in ESSO Specimens," 18th National Symposium on X-Ray Study on Deformation and Fracture of Solids, The Soc. of Mat'l. Science, Japan, July 13-14, 1981.
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5.5 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.5 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.5 CRACK ARREST TECHNOLOGY

SUBTASK/MILESTONE	FY 83				FY 1984									FY 85				FY 86	FY 87	Beyond FY 87								
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1				2	3	4					
H.5.1 <u>Analytical Methodology and Computer Programs</u>																												
A. Complete Dynamic Analysis of Existing Wide-Plate K_{Ia} Specimens for Test Definition																												
a. Complete analysis of Japanese tests																												
b. Develop recommended test specimen design and instrumentation																												
B. Complete Analysis of A533B Base-Metal Wide-Plate Tests and Comparisons with Data																												
a. Complete pretest (state-of-the-art) analyses and input for definition of test conditions																												
b. Complete posttest analyses and comparisons between test data and analyses																												
C. Complete Analyses of Low Upper-Shelf Weld Wide-Plate K_{Ia} Tests																												
a. Complete pretest analyses and definition of test conditions using interim results of Milestone H.2.1.E.d as appropriate																												

MILESTONE STATEMENT AND SCHEDULE

Task: H.5 CRACK ARREST TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4			
A. Publish Report on Standardized K_{Ia} Test Recommendation (University of Maryland) (continued)																							
c. Obtain test results from round-robin participants																							
d. Complete analysis of data and evaluate applicability of method																							
B. Complete Selection of a Laboratory Test Specimen and Procedures for Obtaining K_{Ia} Data at High Toughness in Rising Material Toughness Field (ORNL and BCL) (coordinated with H.3.3.C)																							
a. Identify candidate specimens																							
b. Complete analytical and experimental evaluation of candidate specimens																							
c. Develop data base for PTSE-1 type material																							
d. Complete comparisons between available laboratory and base specimen data																							

MILESTONE STATEMENT AND SCHEDULE

Task: H.5 CRACK ARREST TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87			
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4						
C. Issue Report on Analyses of Low Upper-Shelf Weld Wide-Plate K_{Ia} Tests (continued)																										
b. Complete posttest analyses and comparisons between test data and alternative analyses (see Milestone H.5.3.C)																										
D. Complete Analyses of Wide-Plate K_{Ia} Tests with A533B Steel Heat Treated to Simulate PTSE-1																										
a. Complete pretest analyses and definition of test conditions																										
b. Complete posttest analyses and comparisons between test data and alternative analyses (see Milestone H.5.3.D)																										
H.5.2 <u>Specimen and Test Recommendation</u>																										
A. Publish Report on Standardized K_{Ia} Test Recommendation (University of Maryland)																										
a. Assist in production of draft ASTM standard test method																										
b. Distribute material on ASTM round-robin verification of test method																										

MILESTONE STATEMENT AND SCHEDULE

Task: H.5 CRACK ARREST TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984								FY 85				FY 86	FY 87	Beyond FY 87						
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
H.5.3 Crack Arrest Experiments																									
A. Complete Small-Specimen Crack Arrest Tests to Support Structural Tests and Analyses (BCL)							a,b		c						d				e						
a. Low upper-shelf weld for ITV-8A and A533B steel for PTSE-1																									
b. A508 steel for TSE-7																									
c. A533B steel for WP-1																									
d. Low upper-shelf weld for PTSE-2 and TSE-8																									
e. Base material for PTSE-3																									
B. Complete Series of Wide-Plate K_{Ia} Tests to Near the Upper-Shelf Temperature for Quenched and Tempered A533B GR B Steel (Series WP-1)							a			b,c		d	e												
a. Select test site																									
b. Complete developmental tests																									
c. Complete specimen preparations																									
d. Complete three highly instrumented tests																									
e. Complete three tests with standard instrumentation																									

MILESTONE STATEMENT AND SCHEDULE

Task: H.5 CRACK ARREST TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87			
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4						
C. Complete Series of Wide-Plate K_{Ia} Tests Near the Upper-Shelf Temperature for Low Upper-Shelf Weld (WP-2)																										
a. Procure low upper-shelf weld material and fabricate test specimens (see Milestone H.9.4.B.a and H.10.4.B.b)																										
b. Complete first series of three tests																										
c. Complete second series of three tests																										
D. Complete Series of Six Wide-Plate Tests Near the Upper-Shelf Temperature for A533B Steel Heat Treated to Simulate PTSE-1 (Series WP-3)																										
E. Maintain Computerized Crack-Arrest Data Base (BCL)																										
a. Complete initial data collection																										
b. Enter data through FY 1983																										
c. Enter data through FY 1984																										

6. HSST TASK H.6 IRRADIATION EFFECTS STUDIES

6.1 Objective

The objective of Task H.6 is to determine the effects of neutron irradiation on the fracture toughness properties of typical nuclear reactor pressure vessel (RPV) materials, including plate, forgings, welds, and stainless steel cladding. The properties of interest include fracture initiation toughness (K_{IC} and J_{IC}), crack arrest toughness, (K_{Ia}), ductile tearing resistance (dJ/da), Charpy V-notch (C_v) impact energy, drop-weight NDT, and tensile properties.

6.2 Background

In 1972, the Heavy-Section Steel Technology Program began the first irradiation series in response to the need for information regarding the effects of neutron irradiation on the mechanical properties, particularly fracture toughness, of light-water nuclear reactor pressure vessels. Much research had already been performed in the area of linear elastic fracture mechanics (LEFM) and the effects of specimen size and temperature were known.

The Welding Research Council (WRC) published WRC Bulletin 175 (Ref. 1) in August 1972 and established a reference stress intensity (K_{IR}) curve that was constructed as a lower-bound to K_{IC} , K_{Id} , and K_{Ia} data available for A533 grade B class 1 and A508 steels. This curve was incorporated into the ASME Code and is used as a guideline for operation of reactors to provide protection against nonductile fracture. The effects of irradiation on initiation fracture toughness (K_{IC} and K_{Id}) were not so well understood. A summary of the HSST irradiation series that have been or plan to be undertaken to improve such understanding is shown in Table 6.1. The work breakdown structure for this task is shown in Fig. 6.1 and it is organized around those series.

Series 1 examined static and dynamic fracture toughness with 100-mm (4TCS) compact specimens. That size was determined to be the maximum that could be efficiently used relative to neutron damage symmetry, gamma heating, etc. Both base plate and submerged-arc weld metal were used. The results of Series 1 showed that fracture initiation toughness versus test temperature curves shifted to higher temperatures by an amount approximated by the shift in C_v test results and that fracture initiation toughness reached high values at the higher test temperatures even after irradiation. However, few specimens of the larger sizes were irradiated and tested; and statistical analysis was not possible.

Series 2 and 3 were conducted to examine the effects of irradiation on the ductile-shelf toughness of submerged-arc welds fabricated with high copper levels and older commercial processes that resulted in a fairly low Charpy upper-shelf energy. The motivation for looking at the upper shelf is the requirement in Appendices G and H of Part 10 CFR50 that the Charpy upper-shelf energy must not fall below 68 J (50 ft-lb) as determined from surveillance specimens. In addition to Charpy impact and tensile specimens, compact specimens ranging from 12 to 100 mm were

Table 6.1. Summary of heavy-section steel technology (HSST) irradiation program - March 1983

HSST irradiation series number	Objective	Materials	Total specimen complement	Reactor irradiation dates	Neutron fluence, n/cm^2 ($E > 1$ MeV)	Irradiation temperature, °C (°F)	Comments
1	Upper transition, fracture toughness of plate and weld metal	A533 grade B class 1 (plate 02), submerged-arc weld metal	4TCS - 6 CVCS - 140 CVN - 154 Ten - 34	Battelle Research Reactor, Columbus, Ohio, Westinghouse conducted 10/20/72 to 12/13/73	$2.2-7.0 \times 10^{19}$	270-300 (515-570)	Static and dynamic fracture toughness tests conducted. Status: program completed.
2	Ductile shelf, fracture toughness of low CV shelf material	Low shelf submerged-arc weld metal, 61W, 62W, 63W, Cu: 0.29, 0.21, 0.30%	4TCS - 6 1.6TCS - 6 0.8TCS - 12 0.5TCS - 117 CVN - 207 Ten - 27	Bulk Shielding Reactor, Oak Ridge, Tenn., 10/15/76 to 3/3/77	$0.4-2.1 \times 10^{19}$	233-343 (450-650)	Temperature extremes and lower fluences were for smaller specimens. Status: testing to be completed by 9/83.
3	Ductile shelf, fracture toughness of low CV shelf material	Low shelf submerged-arc weld metal, 64W, 65W, 66W, 67W, Cu: 0.35, 0.22, 0.42, 0.27%	4TCS - 6 1.6TCS - 6 0.8TCS - 12 0.5TCS - 117 CVN - 207 Ten - 27	Bulk Shielding Reactor, Oak Ridge, Tenn., 12/19/77 to 3/29/78	$0.4-1.2 \times 10^{19}$	233-310 (450-590)	Temperature extremes and lower fluences were for smaller specimens. Status: testing to be completed by 9/83.
4	Ductile shelf, fracture toughness of state-of-the-art weld metal	A533 grade B class 1 (plate 02), current practice submerged-arc weld metal, 68W, 69W, 70W, 71W, Cu: <0.10, two FRG materials	ITCS - 240 CVN - 348 Ten - 52	Bulk Shielding Reactor, Oak Ridge, Tenn., 12/18/79 to 7/25/82	$0.5-2.7 \times 10^{19}$	288 (550)	Status: Irradiations completed, testing under way.
5	K_{Ic} curve shift, compare with CVN curve shift; K_{Ic} values high as possible	Submerged-arc weld metals, Cu: 0.25, 0.35%, no copper-coated electrodes, copper added to melt	4TCS - 16 2TCS - 28 1TCS - 60 CVN - 76 Ten - 24 DWT - 16	Planned: Oak Ridge Research Reactor, Oak Ridge, Tenn.,	Target: 2×10^{19}	Target: 288 (550)	Large (8TCS, 6TCS) unirradiated specimens tested to obtain high K_{Ic} values. Status: irradiations being 2/84.
6	Crack arrest toughness	Submerged-arc weld metals, Cu: 0.25, 0.35%, no copper-coated electrodes, copper added to melt	Preliminary: 2TCA - 8 1TCA - 16 0.5TCA - 30	Planned: Oak Ridge Research Reactor, Oak Ridge, Tenn.	Target: 2×10^{19}	Target: 288 (550)	Status: Irradiations begin about 8/85.
7	Stainless steel cladding, fracture toughness of submerged-arc stainless steel cladding	309/308 single-wire oscillating and 308 three-wire series arc	Planned: CVN - 110 Ten - 30 0.5TCS - 48	Planned: Nuclear Science and Technology Facility, Buffalo, New York	Target: 1, 2, and 5×10^{19}	Target: 288 (550)	Status: Irradiations begin 5/83.

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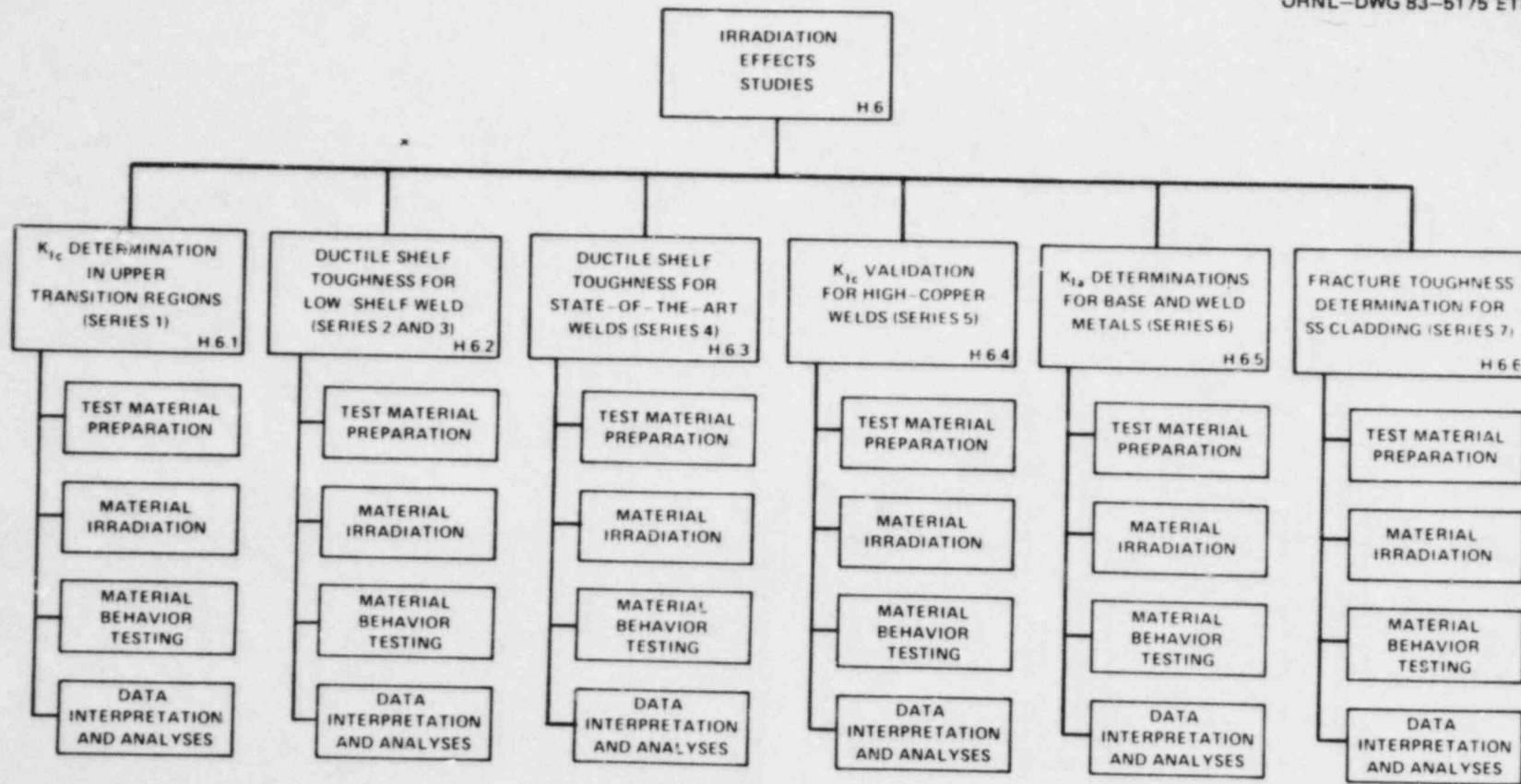


Fig. 6.1 Work breakdown structure for HSST Task H.6 Irradiation Effects Studies.

tested to determine toughness using elastic-plastic test and analysis techniques. The results of Series 2 and 3 showed that the tearing modulus, as measured by elastic-plastic test and analysis, can decrease to very low values after irradiation and can be approximated by the decreases in Charpy impact test upper-shelf energies. These analyses and correlation efforts are still in progress.

Series 4 is also a ductile shelf study except that submerged-arc welds fabricated with low copper content and current practice welding procedures were examined as well as the same plate material (HSST plate 02) used in Series 1. Low upper-shelf materials from the Federal Republic of Germany are included in that study. Series 4 includes only 25-mm-thick compact specimens (1TCS) in addition to the Charpy and tensile specimens. Sufficient specimens exist to perform a statistical analysis of the results, a factor which was lacking in the previous series. The irradiations were completed in 1982 and testing is under way. The testing program is a cooperative effort between ORNL and Materials Engineering Associates (MEA).

Series 5 was conceived to validate the amount and shape of the K_{IC} curve shift as a consequence of neutron irradiation. Currently, estimates of the K_{IC} curve shift are based on results from Charpy impact testing with the assumption that the shift of the Charpy toughness curve to higher temperatures can be applied directly to the K_{IC} curve. This is much the same as the objectives of Series 1 except that sufficient specimens of various sizes up to 100 mm thick will be tested to allow for statistical analysis. Also, drop-weight specimens will be included in the irradiation program. It is not yet known where they will be tested. Submerged-arc welds are being fabricated for inclusion in this series with two weld metals containing different, high-copper contents. The copper was added to the melt before being drawn into wire to provide a uniform copper content in the weld metal, compared to the less-uniform distribution obtained with copper-coated wire.

Series 6 will determine the effect of irradiation on the pressure vessel material's ability to arrest a rapidly propagating flaw. The long-awaited development of an ASTM test method for determining crack arrest fracture toughness, K_{Ia} , has now led to a draft standard; and this has prompted the planning for Series 6 as a natural follow-on to Series 5 on crack initiation. The submerged-arc weldments used for Series 5 will also be used for Series 6. Crack arrest toughness is considered by many to represent the minimum toughness of a material, and it is essential that the effects of irradiation on that property be understood.

Series 7 is designed to determine the effects of irradiation on pressure vessel stainless steel cladding. Cladding is applied to the reactor vessel to minimize corrosion products in the coolant. Analyses of certain thermal-shock scenarios have been inhibited by a lack of information regarding the fracture resistance of the cladding. The little information available in the literature indicates that stainless steel cladding may undergo severe embrittlement as a consequence of neutron irradiation. The plan for Series 7 includes submerged-arc cladding applied by the single-wire oscillating and the three-wire series arc processes. Charpy impact, precracked Charpy, tensile, and 12.5 mm compact specimens (0.5TCS) will be utilized.

6.3 Plan of Action

6.3.1 Series 1

This program is completed.

6.3.2 Series 2 and 3

The only tests remaining on these series are tensile tests from Series 3. The bulk of those tests will be completed in early FY 1984. Series 2 tensile tests were reported by Westinghouse Hanford in 1980.² A few specimens from each weld of Series 3 will be retained for testing with extensometry to obtain stress-strain information in addition to determinations of strength and ductility. A comprehensive report will be prepared to describe the results and analyses.

6.3.3 Series 4

The irradiations were completed in July 1982. The testing is now under way at both ORNL and MEA in accordance with the test plan described below.

In response to Nuclear Regulatory Commission requests, testing of specimens from capsules A, B, and C of the Fourth HSST Irradiation Study are being conducted by two laboratories, ORNL and MEA. Testing by MEA is conducted at the Nuclear Science and Technology Facility of the State University of New York at Buffalo. The plan provides for an approximately equal division of testing between the two facilities.

The primary objective of the Fourth HSST Irradiation Study is to provide statistical data on elastic-plastic fracture toughness (upper-shelf toughness) of nuclear pressure vessel steels and welds. The plan provides for at least half of the testing to be conducted at "upper-shelf" temperatures. In order to provide data for statistical analyses, the test plan also provides for five Charpy impact tests and five ITCS tests of each material at each of six selected test temperatures unless fewer specimens are available.

The bulk of the preliminary Charpy impact tests from capsules A, B, and C have been conducted by ORNL and MEA. Statistical analyses and interpretive activities are under way.

Test temperatures for ITCS specimens will be chosen as follows: (1) NDT temperature [from Charpy 41-J (30-ft-lb) transition temperature] or less such that a valid K_{IC} is obtained, (2) high in the "transition" range (J-R test), (3) "upper knee," and (4) three equally spaced temperatures on the "upper shelf," the highest test temperature being 288°C (550°F).

Two tensile tests will be conducted at each test temperature. The tests will be conducted from about the NDT temperature (Charpy 30-ft-lb transition temperature) to 288°C (550°F). Additional test pairs will be conducted at temperatures spaced approximately equally between the minimum and maximum test temperatures.

The planned testing sequence is as follows:

1. Preliminary Charpy impact tests to determine the probable 41-J transition temperature and "upper-knee" temperature. This has been completed for HSST-02 (A533B-1) and the four welds, both irradiated and control.
2. Complete the Charpy impact tests. Since there are a limited number of control C_v specimens of weld 68W, these tests should be conducted after tests on the other welds have been completed.
3. Tensile tests at temperatures selected on the basis of the C_v results.
4. Control (unirradiated) ITCS tests:
 - a. valid K_{Ic} tests
 - b. "upper-shelf" tests (J-R tests)
 - c. "upper-transition" tests (K_J tests)
 - d. "upper-knee" tests (J-R tests)
5. Irradiated ITCS tests:
 - a. valid K_{Ic} tests
 - b. "upper-shelf" tests (J-R tests)
 - c. "upper-transition" tests (K_J tests)
 - d. "upper-knee" tests (J-R tests)

Results obtained at any point in this test sequence may require modification of the test plan. The investigators will have the option of making such modifications as required to maximize the value of the results.

6.3.4 Series 5

6.3.4.1 Objectives. The primary objective of this program is to obtain valid fracture toughness (K_{Ic} curves for two nuclear pressure vessel materials irradiated at 288°C (550°F). The largest practical compact specimen that can be irradiated is a 4TCS. In the irradiated condition, a 4TCS specimen of these materials can measure K_{Ic} to a level of about 130 MPa \sqrt{m} (120 ksi $\sqrt{in.}$). Smaller specimens (2T and 1TCS) would be employed to measure valid K_{Ic} values down to about 50 MPa \sqrt{m} (45 ksi $\sqrt{in.}$).

In support of the primary objective, there are several supporting objectives necessary to realizing the potentials of this program. These supporting objectives include the following:

1. Unirradiated K_{Ic} data for the two irradiated materials. Large specimens (8TCS) will be required for measurement of a valid K_{Ic} of 130 MPa \sqrt{m} in the unirradiated material. Smaller specimens (6T, 4T, 2T, and 1TCS) would be employed for the lower K_{Ic} levels.
2. Both unirradiated and irradiated 1T and 2TCS specimens would be tested by the J-integral method to provide K_J data above the valid K_{Ic} capacity of these specimen sizes. These data would

help assure valid test results for the more expensive (and valuable) larger specimens and would also provide a much needed comparison of K_J results with K_{IC} results.

3. Tensile properties of unirradiated and irradiated materials will provide data both for determining test parameters for the fracture toughness tests and for analysis of the fracture toughness data.
4. Charpy V-notch impact tests of unirradiated and irradiated materials will provide data to guide the setting of fracture toughness test parameters and correlate radiation-induced shifts of C_v transition temperature with radiation-induced shifts of the K_{IC} curves. Drop-weight tests will be used to index the nil-ductility temperature (NDT) of the Charpy curve for unirradiated and irradiated materials.

The test plan will provide for statistical analysis of the results insofar as is practical.

6.3.4.2 Materials. A radiation-induced temperature shift of toughness properties (C_v transition temperature and K_{IC} curve) of 85°C (150°F) will provide a significant and meaningful separation of the unirradiated and irradiated properties. The radiation-induced shifts of RPV materials are functions primarily of fast-neutron fluence, irradiation temperature, and copper content of the steels. Since an irradiation temperature of 288°C (550°F) has been chosen as most significant for both the industry and regulatory bodies, the most practical fast-neutron fluence and copper contents must be selected. The target fast-neutron fluence will be 2×10^{23} n/m² ($E > \text{MeV}$). Two submerged arc weldments with nominally A533 grade B composition are being fabricated for this program; the target copper contents are 0.25 and 0.35%. The weldments will be fabricated and stress-relieved according to commercial practice in 216-mm-thick plate. About 14 lin m of each weldment will be fabricated for the program.*

6.3.4.3 Specimen complement. The valid K_{IC} measuring capacity of a compact specimen is a function primarily of yield stress and specimen thickness. The yield stress for the unirradiated submerged-arc weldments should be about 480 MPa (70 ksi) and about 620 MPa (90 ksi) for the irradiated material. Valid fracture toughness tests will be conducted at five target toughness levels and, therefore five estimated test temperatures relative to the NDT. The specimen sizes (K_{IC} and K_J) and number of specimens for each toughness level (and estimated test temperature) are presented in Table 6.2 for unirradiated and irradiated materials. The complement of Charpy V-notch, miniature tensile (MT), standard tensile, and drop-weight specimens is presented in Table 6.3.

The number of specimens listed in Tables 6.2 and 6.3 are per material: the total numbers of specimens are twice the numbers listed. The numbers of specimens specified are based on a consideration of statistical requirements and within the constraints of probable irradiation facilities.

*This amount of weldment will also provide material for the Series 6 program on irradiation effects on crack arrest (K_{Ia}); see Section 6.3.5.

Table 6.2. Compact specimen complement^a
for K_{Ic} curve shift program

Target K_{Ic} , MPa \sqrt{m} (ksi $\sqrt{in.}$)	49 (45)	66 (60)	88 (80)	110 (100)	132 (120)	Totals per material
Estimated relative test temperature, T-NDT, °C (°F)	-56 (-100)	-14 (-25)	3 (5)	11 (20)	19 (35)	
<u>Unirradiated</u>						
K_{Ic} , 1T-CS (valid tests)	10					10
K_{Ic} , 2T-CS (valid tests)		4				4
K_{Ic} , 4T-CS (valid tests)			4			4
K_{Ic} , 6T-CS (valid tests)				2		2
K_{Ic} , 8T-CS (valid tests)					2	2
K_J , 1T-CS		6	6	6	6	24
K_J , 2T-CS			4	4 ^b	4 ^b	12
K_J , 4T-CS				4 ^b	4 ^b	8 ^b
<u>Irradiated</u>						
K_{Ic} , 1T-CS (valid tests)	4	8				12
K_{Ic} , 2T-CS (valid tests)			6			6
K_{Ic} , 4T-CS (valid tests)				4	4	8
K_J , 1T-CS			6	6	6	24
K_J , 2T-CS				4	4	8

^aNumber of specimens per material.

^bThese tests would be valuable if material is available.

6.3.4.4 Test plan. Two organizations, MEA and ORNL, will participate in the testing program. Because the testing equipment has limitations, all testing of irradiated 4TCS specimens and unirradiated 6TCS and 8TCS specimens will be conducted by MEA and all tensile tests, unirradiated and irradiated, will be conducted by ORNL. Due to cost considerations (MEA does not have out-of-cell test facilities), about 75% of the Charpy testing will be conducted at ORNL. All material characterization will be conducted at ORNL. A fraction of the unirradiated specimens, C_v , 1T- K_{Ic} , and 1T- K_J , will be retained for testing with the corresponding irradiated specimens.

The testing sequence is as follows:

1. Materials inspection and characterization, including ultrasonic inspection, chemical analyses, metallurgical structure studies, standard tensile tests, drop-weight tests, and preliminary C_v tests.
2. Testing of a major fraction of unirradiated specimens:
 - a. C_v tests,
 - b. tensile tests,

Table 6.3. Charpy V-notch impact, drop-weight and tensile specimens^a
for K_{Ic} curve shift program

Estimated test temperature relative to NDT (T-NDT)		Charpy-V specimens		Drop-weight specimens	Tensile specimens		
		Unirradiated	Irradiated		Unirradiated		Irradiated, MT
(°C)	(°F)				Standard	MT	
Room temperature survey tests ^b		16	13	12 ^c	4		
-56	-100					6	3
-28	-50	5				6	3
-14	-25						
0	0	10	10			6	3
24	35						
40	70	10	5				
70	125	10	5			6	3
111	200	10					
167	300	10	5				
222	400	10					
Totals (per material):		81	38	24	4	24	12

^aNumber of specimens per material.

^bVaried temperatures to determine NDT and "upper-knee" temperatures.

^cNumbers shown are same for unirradiated and irradiated.

- c. J_{Ic} (K_J) tests of ITCS specimens,
 - d. K_{Ic} tests of ITCS specimens,
 - e. J_{Ic} (K_J) tests of 2TCS specimens,
 - f. K_{Ic} tests of 2TCS specimens,
 - g. J_{Ic} (K_J) tests of 4TCS specimens,
 - h. K_{Ic} tests of 4TCS specimens, and
 - i. K_{Ic} tests of 6TCS and 8TCS specimens.
3. Testing of irradiated specimens and remainder of unirradiated specimens:
- a. C_v tests,
 - b. tensile tests,
 - c. drop-weight tests,
 - d. J_{Ic} (K_J) tests of ITCS specimens,
 - e. K_{Ic} tests of ITCS specimens,
 - f. J_{Ic} (K_J) tests of 2TCS specimens,
 - g. K_{Ic} tests of 2TCS specimens, and
 - h. K_{Ic} tests of 4TCS specimens.

All irradiations are planned for the Oak Ridge Research Reactor poolside facility. A prototype 4T capsule has been designed and tested to provide information for dosimetry analyses and thermal shield design.

6.3.5 Series 6

6.3.5.1 Objectives. The primary objective of this series is to obtain valid crack arrest toughness (K_{Ia}) curves for two nuclear pressure vessel materials irradiated at 288°C. Supporting objectives include the following:

1. The existing K_{Ia} data base for unirradiated and irradiated materials will be enlarged.
2. The upward temperature shift and the shape of the K_{Ia} curve, relative to RT_{NDT} , due to irradiation will be verified.
3. The K_{Ia} results will complement the K_{Ic} results obtained with the same well characterized material.
4. Lower-bound data will be obtained for analysis of the K_{IR} curve under irradiated conditions.

6.3.5.2 Materials. The materials for this series are the same submerged-arc weldments used for the K_{Ic} program of Series 5.

6.3.5.3. Specimen complement. As with K_{Ic} , the valid K_{Ia} measuring capacity of a compact crack arrest (CCA) specimen is a function primarily of yield stress and specimen thickness. The yield stress for the unirradiated submerged-arc weldments should be about 480 MPa (70 ksi) and about 620 MPa (90 ksi) for the irradiated material. A 50-mm-thick CCA specimen (2TCCA) can provide a "valid" K_{Ia} measurement up to about $187 \text{ MPa}\sqrt{\text{m}}$ ($170 \text{ ksi}\sqrt{\text{in.}}$) for the irradiated material and about $145 \text{ MPa}\sqrt{\text{m}}$ ($132 \text{ ksi}\sqrt{\text{in.}}$) for the unirradiated material. A 3TCCA specimen can measure up to about $190 \text{ MPa}\sqrt{\text{m}}$ for unirradiated material, about the same as that for the irradiated 2TCCA specimen.

The specimen complement is preliminary, but currently we envision three capsules will be irradiated in two series. The first capsule will contain the 0.5TCCA (30) and ITCCA specimens while the second and third capsules will contain the 2TCCA (9 each) specimens. The small specimen capsule will be irradiated first by itself, and the large specimen capsules will be irradiated together. This complement should provide enough specimens to allow for statistical analyses in the same manner as Series 5. The number of specimens given for each size is the total to be divided as equally as possible for two materials.

6.3.5.4 Test plan. The testing organizations have not been chosen for this series, but they will likely be ORNL and one other. All material characterization will be performed by ORNL as part of the Series 5 program. All irradiations are planned for the Oak Ridge Research Reactor poolside facility. The testing plan is yet to be formulated, but it will generally follow the concept of testing small specimens to establish likely test temperatures for the larger specimens. Test procedures will follow the latest ASTM standard available at the time.

6.3.6 Series 7

6.3.6.1 Objectives. The objective of this series is to obtain toughness properties for two types of stainless steel cladding in the unirradiated and irradiated conditions. The properties to be obtained include tensile, Charpy V-notch impact, and J-integral toughness (using precracked Charpy specimens and 0.5TCS specimens). The goal is to evaluate irradiated weld-metal cladding representative of that used in early PWRs that are being evaluated for their fracture resistance under over-cooling situations.

6.3.6.2 Materials. The materials for this study are stainless steel claddings, nominally type-308, deposited on A533, Grade B, class 1 steel plate using two weld cladding procedures. The cladding and stress relief treatment will duplicate commercial procedures as closely as possible. However, to permit fabrication of mechanical test specimens of the cladding, cladding thickness will be about 15 mm, obtained by multi-layer deposition of the cladding. This is thicker than the usual pressure vessel cladding thickness (4 to 6 mm), but it should represent multi-layer cladding. Materials will be characterized by welding parameters, chemical composition, metallographic examination, and mechanical properties.

The two weld cladding procedures chosen for this study are the single-wire oscillating procedure and the three-wire series-arc procedure. The primary differences between these procedures is in heat input and the resulting amounts of base metal dilution of the stainless steel cladding. The single-wire cladding has already been fabricated and partially characterized.

In the single-wire oscillating procedure, the first layer of cladding is deposited using type-309 weld wire and additional layers are deposited using type-308. In this instance, this procedure used high heat input during welding and resulted in considerable base metal dilution of the lower layers of cladding. Both the cladding near the base metal (higher dilution) and the top layers of cladding (little dilution) will be studied. This material has been fabricated at ORNL with the

identical weld wire, flux, welding conditions, and heat treatment as used for fabrication of the clad beams for the "cladding evaluation program" (Task H.7). Irradiation of the first two groups of specimens has been completed.

In the three-wire series-arc procedure, separate weld wires of types 308, 309, and 312 stainless steel are independently fed into the welding arc. Feed rates for each wire are adjusted to obtain the desired cladding composition. This procedure uses low heat input and results in low base metal dilution of the stainless steel cladding. A contract has been placed with Combustion Engineering Corporation for preparation of the three-wire series-arc clad test plate with delivery expected in early FY 1984.

6.3.6.3 Specimen complement. Charpy V-notch, precracked Charpy, miniature tensile, and 0.5TCS specimens have been or will be fabricated. Irradiation capsules will contain either 20 Charpy (V-notch or precracked) and six tensile specimens or twelve 0.5TCS specimens.

6.3.6.4 Test plan. Table 6.4 presents the cladding irradiation program summary. The first two capsules contained C_v and tensile specimens, type 309 (bottom layer) in one capsule and type 308 (top layer) in the other, and they were irradiated to a fluence of 2×10^{23} n/m². The irradiations are conducted by MEA in the Nuclear Science and Technology Facility (NSTF) reactor at the University of Buffalo. The NRC currently has a dosimetry program under way for core positions B4 and C2 in the NSTF, and it is those core positions that have been specified for the cladding irradiations. Charpy impact specimens will be tested to obtain a full toughness curve with testing up to 288°C. Tensile specimens will be tested from room temperature to 288°C. A capsule of 0.5TCS specimens from the single-wire clad material is also planned for later in the program and will be irradiated if the C_v results indicate significant degradation of toughness.

Table 6.4. Cladding irradiation program summary

Capsule	Type cladding	Specimen complement	Target fluence (n/cm ²)
A	1-wire, type 309	20 C_v , 6 tensile	2×10^{19}
B	1-wire, type 308	20 C_v , 6 tensile	2×10^{19}
C	1-wire, type 309/308	12 0.5TCS	2×10^{19}
D	3-wire	20 C_v , 6 tensile	2×10^{19}
E	3-wire	12 0.5TCS	2×10^{19}
F	3-wire	20 C_v , 6 tensile	1×10^{19}
G	3-wire	12 0.5TCS	1×10^{19}
H	3-wire	20 C_v , 6 tensile	5×10^{19}

The three-wire cladding from Combustion Engineering will be available in early FY 1984. Current plans for irradiations include C_v and tensile specimens to be exposed to fluences of 1, 2, and 5×10^{23} n/m^2 . The irradiation at 2×10^{23} n/m^2 should be completed by mid-FY 1985 with testing completed by the end of FY 1985. We have also tentatively planned for irradiation of small compact specimens (0.5TCS) from the three-wire cladding to fluences of 1 and 2×10^{23} n/m^2 . The capsule irradiation sequence will be planned so that the results at 2×10^{23} n/m^2 can be used to assess the need for data at 1×10^{23} n/m^2 . The irradiation sequence is presented in Fig. 6.2. A complementary laboratory testing program will be conducted to include the investigation of subsized specimens. The objective of that effort is to ascertain the feasibility of irradiating and testing specimens sectioned from "regular" cladding (i.e., one- or two-layer cladding as normally applied to a vessel for comparison with the full-size specimens sectioned from the "built-up" cladding. Additionally, a similar study will be performed with composite specimens sectioned to allow for notch or crack-tip placement at specific regions within the clad or heat-affected zone.

The recommended testing sequence is as follows:

1. Materials inspection and characterization.
2. Test unirradiated specimens at four temperatures.
 - a. tensile tests,
 - b. C_v tests,
 - c. dynamic PCC_v tests (about half of the PCC_v specimens),
 - d. static bend tests of PCC_v specimens (remainder of PCC_v specimens, and
 - e. J-R tests on 0.5TCS specimens.
3. Test irradiated specimens at four temperatures.
 - a. tensile tests,
 - b. C_v tests

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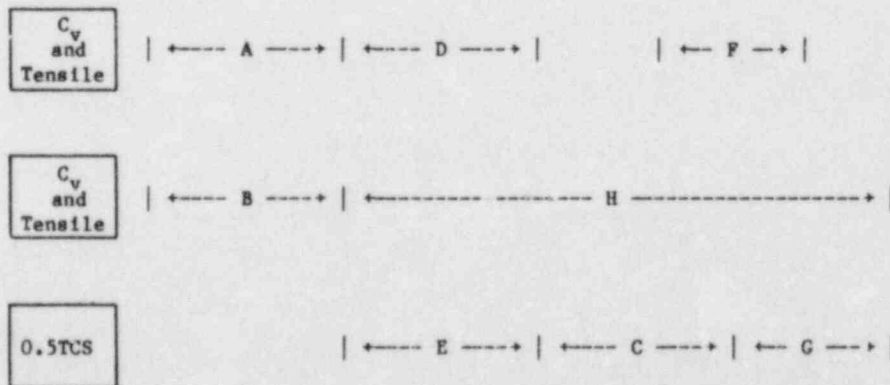


Fig. 6.2 Cladding irradiation sequence. Capsule C will be irradiated if C_v results justify, capsules F and G (1×10^{19} n/m^2) will be irradiated if results of capsules D and E (2×10^{19} n/cm^2) justify.

- c. dynamic PCC_v tests,
- d. static PCC_v tests, and
- e. J-R tests on 0.5TCS specimens.

A metallurgical study to characterize the material as well as scanning electron fractography to aid in understanding fracture mode under all test conditions are planned in conjunction with the irradiation and testing activities. A clad reactor vessel nozzle cutout has been procured from Combustion Engineering, and the suitability of that material for the testing and irradiation programs will be determined after examination of the cladding thickness.

6.4 References

1. PVRC Ad Hoc Task Group on Toughness Requirements, *PVRC Recommendations on Toughness Requirements*, Welding Research Council, WRC Bulletin 175, August 1972.
2. J. A. Williams, *Tensile Properties of Irradiated and Unirradiated Welds in A533 Steel Plate and A508 Forgings*, NUREG/CR-1158, HEDL-TME-7951, Hanford Engineering Development Laboratory, Richland, Washington, January 1980.

6.5 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.6 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.6 IRRADIATION EFFECTS STUDIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984									FY 85				FY 86	FY 87	Beyond FY 87						
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4						
B. Issue Report on Series 4 – Capsules A, B, and C (continued)																										
d. Complete interpretations																										
C. Issue Report on Series 4 – Capsule D (FRG)																										
a. Complete analysis of CVN data																										
b. Complete analysis of 1TCS data																										
c. Compare predictions and data																										
d. Complete interpretations																										
H.6.4 K_{IC} Validation for High-Copper Welds (Series 5)																										
A. Complete Test Material Preparation																										
a. Complete procurement of materials																										
b. Complete fabrication of welds																										
c. Fabricate specimens – capsules 1 through 4																										
d. Fabricate specimens – capsules 5 through 12																										
B. Complete Material Irradiations																										
a. Complete 4TCS dummy capsule verification test																										
b. Complete 4TCS capsule design																										

MILESTONE STATEMENT AND SCHEDULE

Task: H.6 IRRADIATION EFFECTS STUDIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87	
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
B. Complete Material Irradiations (continued)																								
c. Complete small specimen capsule design																								
d. Capsules 1 through 4 (4TCS)																								
e. Capsule 5 (CVN, tensile, 1TCS)																								
f. Capsule 6 (DWT)																								
g. Complete 2TCS capsule design																								
h. Capsules 7 and 8 (2TCS)																								
i. Capsules 9 through 12 (4TCS)																								
C. Complete Specimen Testing																								
a. Complete unirradiated CVN, tensile, and DWT tests																								
b. Complete irradiated CVN, tensile, and DWT tests																								
c. Complete unirradiated compact specimen tests - 1T, 2T, 4T, 6T, and 8T																								
d. Complete irradiated compact specimen tests - 1T, 2T, and 4T																								
D. Issue Final Report on Series 5																								
a. Complete analysis of CVN and DWT data																								

MILESTONE STATEMENT AND SCHEDULE

Task: H.6 IRRADIATION EFFECTS STUDIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984								FY 85				FY 86	FY 87	Beyond FY 87					
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
D. Issue Final Report on Series 5 (continued)																								
b. Complete analysis of compact specimen data																								▽
c. Compare predictions and data																								▽
d. Complete interpretations																								▽
H.6.5 <u>K_{1a} Determinations for Base and Weld Metals (Series 6)</u>																								
A. Complete Test Material Preparation																								
a. Complete procurement of materials (see H.6.4.A.a)																								
b. Complete fabrication of welds (see H.6.4.A.b)																								
c. Select CA specimen design and complement																								
d. Fabricate CA specimens																								
B. Complete Material Irradiations																								
a. Complete CA capsule design																								
b. Capsules A and B																								
c. Capsule C																								
C. Complete Specimen Testing																								
a. Complete development of remote CA test facility																								
b. Complete unirradiated CA tests																								

MILESTONE STATEMENT AND SCHEDULE

Task: H.6 IRRADIATION EFFECTS STUDIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87	
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
C. Complete Specimen Testing (continued)																								
c. Complete irradiated CA tests																								
D. Issue Report on Series 6																								
a. Complete analysis of CA data																								
b. Compare predictions and data																								
c. Complete interpretations																								
H.6.6 <u>Fracture Toughness Determination for Stainless Steel Cladding (Series 7)</u>																								
A. Complete Test Material Preparation	a	b																						
a. Complete procurement of one-wire clad																								
b. Fabricate CVN and tensile specimens of one-wire clad - capsules A and B																								
c. Complete procurement of three-wire clad (see Milestone H.3.1.H.c)																								
d. Fabricate compact specimens of one-wire clad - capsule C																								
e. Fabricate CVN, tensile, and compact specimens of three-wire clad - capsules D, E, F, G, and H																								

MILESTONE STATEMENT AND SCHEDULE

Task: H.6 IRRADIATION EFFECTS STUDIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4	86	87			
B. Complete Material Irradiations				▼ ^a														▼ ^b	▼ ^c	▼ ^d	▼ ^{e, f}				
a. Capsules A and B (one-wire CVN, and tensile) - 2×10^{23} n/m ²				▼																					
b. Capsules D (three-wire CVN and tensile) and E (three-wire compacts) - 2×10^{23} n/m ²																		▼							
c. Capsule C (one-wire compacts) - 2×10^{23} n/m ²																			▼						
d. Capsule H (three-wire CVN and tensile) - 5×10^{23} n/m ²																				▼					
e. Capsule F (three-wire CVN and tensile) - 1×10^{23} n/m ²																					▼				
f. Capsule G (three-wire compacts) - 1×10^{23} n/m ²																					▼				
C. Complete Specimen Testing								▼ ^a		▼ ^b								▼ ^c	▼ ^d	▼ ^e	▼ ^f	▼ ^g	▼ ^h		
a. Complete unirradiated one-wire CVN and tensile tests								▼																	
b. Complete irradiated one-wire CVN and tensile tests (2×10^{23} n/m ²)										▼															
c. Complete unirradiated three-wire CVN and tensile tests																		▼							
d. Complete irradiated three-wire CVN and tensile tests (2×10^{23} n/m ²)																				▼					

MILESTONE STATEMENT AND SCHEDULE

Task: H.6 IRRADIATION EFFECTS STUDIES (continued)	FY 83			FY 1984												FY 85			FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2				3	4
C. Complete Specimen Testing (continued)																							
e. Make decision concerning necessity for irradiation and/or testing of capsules C, E, F, G, and H																							
f. Complete unirradiated one- and three-wire compact tests																							
g. Complete irradiated one-wire compacts (2×10^{23} n/m ²) and three-wire CVN and tensile tests (5×10^{23} n/m ²)																							
h. Complete irradiated three-wire compacts (1×10^{23} n/m ²) and three-wire CVN and tensile tests (1×10^{23} n/m ²)																							
D. Issue Report on Series 7																							
a. Complete analysis of one-wire CVN and tensile data - 2×10^{23} n/m ²																							
b. Complete interpretation of one-wire CVN and tensile data - 2×10^{23} n/m ²																							
c. Issue interim report on irradiation effects on one-wire cladding at 2×10^{23} n/m ²																							
d. Complete analysis and interpretation of three-wire CVN and tensile data - 2×10^{23} n/m ²																							

MILESTONE STATEMENT AND SCHEDULE

Task: H.6 IRRADIATION EFFECTS STUDIES (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87	
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
D. Issue Report on Series 7 (continued)																								
e. Issue interim report on irradiation effects on three-wire cladding at 2×10^{23} n/m ²																								
f. Complete analysis and interpretation of one-wire compacts at 2×10^{23} n/m ² , three-wire CVN and tensile data at 5×10^{23} n/m ²																								
g. Complete analysis and interpretation of three-wire compacts at 1×10^{23} n/m ² and three-wire CVN and tensile tests at 1×10^{23} n/m ²																								

7. HSST TASK H.7 CLADDING EVALUATIONS

7.1 Objective

The objective of Task H.7 is to demonstrate the effect of stainless steel weld cladding on the extent of crack propagation, for a small surface crack subjected to a stress gradient similar to that produced by a thermal shock.

7.2 Background

The Cladding Evaluations Task of the HSST Program was initiated to study the interaction of stainless cladding with flaws initiated in and propagating in base metal. From the designer's viewpoint stainless cladding is primarily viewed as a corrosion- and crud-prevention material in light-water reactor vessel design and except for its effect upon fatigue in thermal transients, its effect upon structural integrity has heretofore been largely disregarded. With the more recent focus of safety studies upon LOCA scenarios that emphasize the behavior of small flaws, it has become evident that stainless cladding may have a key role in the propagation and/or arrest of propagating flaws. Complicating factors which seriously affect an understanding of the role stainless cladding plays in flaw propagation are its fracture toughness as a function of irradiation dose and the influence of several fabrication processes that have been used in vessel fabrication. Meager data exist in both of these areas. The initial phase of this study has attempted to address this question by testing stainless-clad specimens that had been subjected to heat treatments to simulate "beginning-of-life" and "end-of-life" toughness conditions to fast-running cracks. The work breakdown structure for this task has been organized around the type of cladding being investigated as shown in Fig. 7.1.

A survey of fabrication processes employed on reactor vessels revealed that the majority of light-water reactor vessels have employed either three-wire or strip-clad processes with the three-wire process being predominantly used on early vessels, and the strip process on later vessels. Because of the pressing need for data, the mothballing by vendors of their three-wire equipment, and the attendant difficulty in obtaining timely contracts for vendor preparation of specimens, initial specimens used in the HSST program tests were prepared at ORNL by using a single-wire welding procedure.

The specimens were designed as rectangular parallelepipeds with stainless cladding on one face. Grooves were machined in the cladding with the intent to provide a plane surface at the bottom of the groove at the stainless-base metal interface. An electron beam (EB) weld was then applied to the bottom groove surface. Specimens were cooled to the test temperature and were loaded by four-point, constant-moment loading to the stress state required. Hydrogen charging of the EB weld was initiated and presented the stainless cladding with a relatively fast-

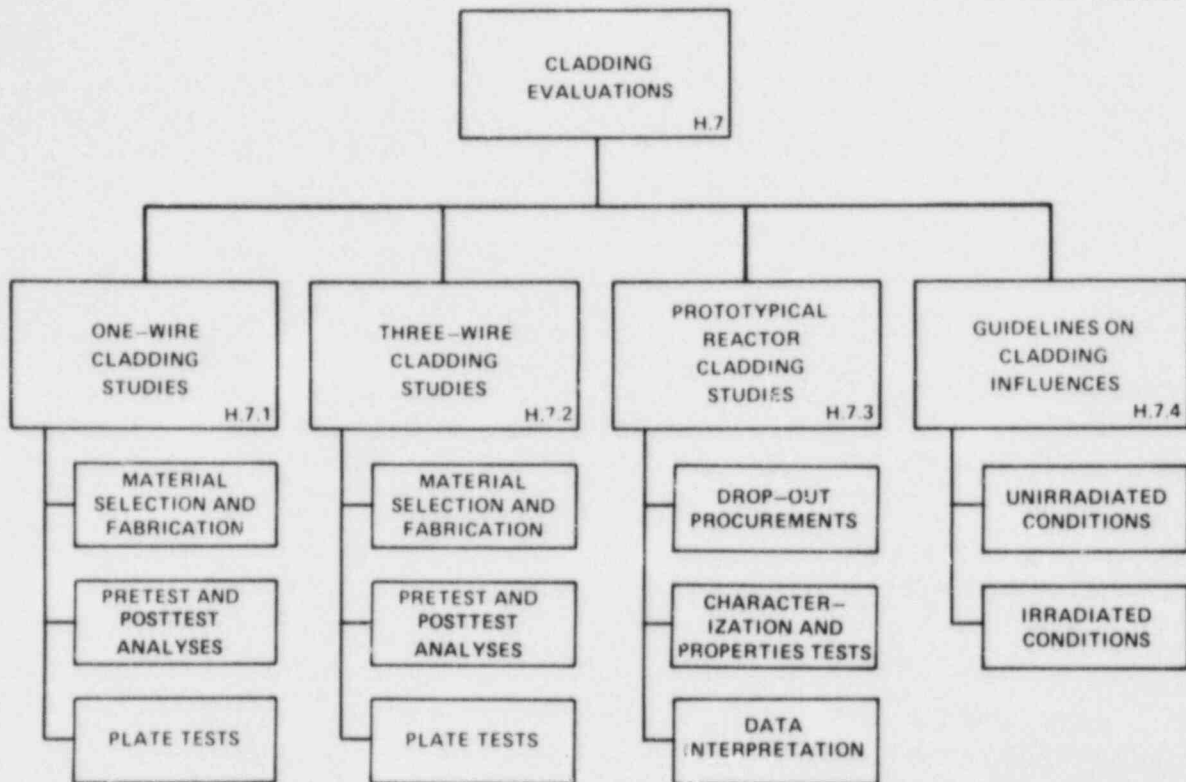


Fig. 7.1 Work breakdown structure for HSST Task H.7 Cladding Evaluations.

running crack. A matrix of specimens was planned that varied the parameters: flaw size, run distance from EB weld to cladding, cladding type, and stress state in order to elucidate cladding arrest behavior.

Problems were experienced with groove machining to obtain the stainless base metal interface, in some cases the groove was too shallow, in others too deep. On specimens where stainless remained below the groove, premature popping of the EB weld prior to hydrogen charging was a common phenomenon, preventing a proper control of the stress state. On specimens with too deep grooves, the geometry caused premature arrest and prevented the flaw from running to the cladding. In addition, the specimens prepared by sigma-phase heat treatment were too brittle and, based on limited data, are not representative, as intended, of end-of-life conditions.

The tests completed to date under the initial phase of this study indicate that the cladding employed to represent beginning-of-life conditions has sufficient arrest toughness to stop running cracks, but the upper and lower bounds of crack arrest are not yet determined. Analyses of the tests by two approximate techniques and by the ORVIRT finite-element methods have not been completely consistent. The fabrication techniques employed for this first series of tests have resulted in conditions that have prevented control of the stress state at pop-in of the

hydrogen-charged EB welds. Consequently, bounding of the arrest toughness of the stainless cladding has been prevented.

Preparations are now under way to redesign and fabricate a new series of specimens that will eliminate the problems presented by the groove/EB weld design of the first series. In addition, this series will employ material prepared by a three-wire weld cladding technique typical of many early reactor vessel designs.

7.3 Plan of Action

A special fabrication subcontract was placed with Combustion Engineering Co., Inc., in July 1983, to produce specimen blanks and characterization material employing a three-wire weld cladding technique typical of many early reactor vessel designs. A special heat treatment procedure will be developed and applied to this material with the purpose of raising the NDT of the base plate while maintaining the room temperature yield strength between 414 and 690 MPa. In addition, the Charpy-impact energy of the cladding shall be at least 54.2 J (40 ft-lb) at a temperature either -7°C (20°F) below the NDT of the base plate or at which the Charpy-impact energy is 27.1 J in the base plate, whichever is lower.

The combination of these material properties will substantially improve the capability of obtaining the crack arrest toughness for this type of cladding for beginning of life conditions. The conditions requisite for obtaining end-of-life cladding arrest toughness values will be based on the results from the Seventh Irradiation Series (see Task H.6) where testing of irradiated specimens of single-wire stainless cladding is scheduled for completion during FY 1984.

Six clad plate specimens and two unclad specimens will be machined in FY 1985 from the blanks furnished by the Combustion Engineering contract. In addition, single layer and multilayer cladding will be obtained for characterization.

A nozzle dropout having a nominal 4.76 mm (3/16 in.) layer of 3-wire stainless cladding was purchased from Combustion Engineering Co., Inc. Tensile and Charpy-impact values are being obtained and photomicrographic studies are being made. Negotiations are also underway to obtain nozzle dropouts with single-wire, six-wire and strip cladding types. Similar studies will be performed on these materials.

A collection of the data from these various sources will provide a basis for more substantive direction of this activity in FY 1986.

7.4 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.7 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.7 CLADDING EVALUATIONS (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87	
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
H.7.3 <u>Prototypical Reactor Cladding Studies</u>																								
A. Complete Characterization Study of RPV Drop-Outs																								
a. Procure drop-outs from RPV manufacturers																								
b. Complete metallographic and properties characterization																								
c. Interpret results in comparison with results from other clad materials																								

8. HSST TASK H.8 INTERMEDIATE VESSEL TESTS AND ANALYSES

8.1 Objective

The objective of Task H.8 is to expose flaws to specific stress states and conditions to (1) demonstrate actual behavior under conditions found in reactor pressure vessels (RPV's) and (2) determine the applicability of theoretical methods to the fracture behavior of RPV's. This is accomplished through testing and analyzing thick pressurized vessels over a full range of fracture characteristics.

8.2 Background

The original plan of the HSST program contemplated that simulated service test would comprise one of the principal program tasks.¹ Simulated service tests were conceived as fracture tests of specimens or structures of dimensions large enough to develop stress states in the region of interest like those in reactor pressure vessels. The general purpose was to demonstrate whether or not fracture mechanics concepts that had been verified experimentally on a small laboratory scale were valid and useful in the fracture analysis of full-size vessels.

The main factors that were expected to be important in relating laboratory-scale fracture to that of large-scale structures were:

- (1) Wall thickness
 - (a) transverse restraint
 - (b) variability of properties
 - (c) flaw location
 - (d) flaw orientation
- (2) Material-embrittling factors
 - (a) temperature
 - (b) irradiation
 - (c) strain aging
 - (d) reversed plastic strain
 - (e) heat treatment, temperature embrittlement, and composition
- (3) Stress analysis
 - (a) crack location, configuration, orientation, and number
 - (b) diameter-to-thickness ratio
 - (c) crack depth-to-thickness ratio
 - (d) biaxiality and stress concentration
 - (e) thermal and residual stresses
- (4) Crack configuration
 - (a) depth
 - (b) shape
 - (c) preparation techniques

The validation of methods for fracture predictions was to proceed in steps from laboratory specimens to intermediate-scale vessels to

full-size pressure vessels. First, the simple transition temperature and fracture mechanics results obtained from more or less standard specimens were to be generalized to thick specimens with varying flaws subjected to tensile loading. Such specimens were to be examined both for tough and frangible behavior. Next, the complexities of pressure vessel geometry were to be introduced on small epoxy and steel models in preparation for tests of flawed intermediate-scale vessels. Finally, tests were to be performed on vessels having the full-scale features of reactor pressure vessels. Practical considerations of limited monetary and other resources eliminated full-scale tests and tests of irradiated models from the plan.

As actually implemented, the intermediate vessel test series (Task H.8) and the thermal-shock (Task H.9) and pressurized thermal-shock (Task H.10) tests constitute the simulated service tests. The test specimens (cylinders or vessels) have been chosen to be thick and long enough to produce stress states in the flawed region that represent the conditions that would be obtained in a reactor pressure vessel. Intermediate test vessels (ITV) are ~150-mm thick, which is the nominal thickness of a boiling-water-reactor vessel. With this thickness and the 1300-mm length of the test section, the ITV's are also excellent fracture-mechanics specimens. Large surface flaws in the beltline region of these vessels are essentially as well restrained as they would be in a reactor pressure vessel. It is important to remember now that, at the inception of the HSST program, there were doubts and apprehension about whether a thick structure would exhibit a "transition temperature" separating frangible and ductile behavior. While that concern was resolved, transverse restraint, and therefore thickness, in fracture behavior is as important a factor as ever. Only in intermediate vessel and thermal-shock tests has transverse restraint been great enough to produce plane-strain conditions with high K_I values in pressure vessel steels.

The program of intermediate vessel tests was, therefore, planned to fulfill the broad objectives of the simulated service tests over the wide variety of conditions that constitute the real operating environments. The main effort of this task was to determine which factors or conditions were important and then to carry out tests with the particular combinations of conditions that would contribute significant information on behavior of structures in service. Factors of concern include material properties; flaw location, orientation, shape, size, and sharpness; and loading and environmental conditions. If expense, resources, safety, and time were of no importance, the significance of these factors could be studied under actual service conditions imposed on vessels in a large number of experiments with vessels as large as, or larger than, reactor pressure vessels. Since such an approach is completely impractical, each factor is studied separately or in combination with others on as simple a scale as practicable.

The objective of each simulated service test has been to provide data from which the ability of analytical methods to predict the fracture behavior of a flawed structure under known conditions of material properties and loading could be assessed. In the planned progression of tests, analytical methods are confirmed, improved, or their limitations revealed. The testing of intermediate vessels in conjunction with

flawed tensile specimens of similar material permits consideration of many variables, such as flaw size, section thickness, temperature, and stress state. The effects of differences in transverse restraint, toughness, plastic strain, biaxiality, and stress concentration can also be observed and analyzed.

The original objectives emphasized in the simulated service tests were (1) to demonstrate capability to predict the "vessel transition temperature" for a selected crack configuration using the material of interest (ASTM A533, grade B, class 1 plate; ASTM A508, class 2 forging); (2) to demonstrate, for the materials of interest, the capability to predict various combinations of load (pressure), temperature, and crack configuration in full-thickness walls (1.52 mm or more) that will not cause fracture, and finally a combination that will cause fracture for both frangible and tough fracture conditions.

The intermediate vessel tests have been divided into four series:

- (1) flaws in cylindrical vessels, A508, class 2 forging steel - two vessels;
- (2) flaws in cylindrical vessels with longitudinal weld seams, A508, class 2 forging steel, submerged-arc welds - three vessels;
- (3) flaws in cylindrical vessels with longitudinal weld seams, A533, grade B, class 1 plate steel, submerged-arc welds - two vessels;
- (4) cylindrical vessels with radially attached nozzles, vessels of A508, class 2 forging steel and A533, grade B, class 1 plate steel; nozzle of A508, class 2 forging steel - three vessels.

Test conditions were selected to produce fracture toughnesses ranging from the low transition to the fully ductile upper shelf. The variations of test conditions, flaw configurations, materials, and stress states are summarized in Table 8.1. The scope of the activities necessary to carry out the tests and analyses is illustrated in the work breakdown structure, which is shown in Fig. 8.1.

Most of the tests in the original plan have been performed, including the supporting research.²⁻⁵ An extensive series of epoxy and steel model tests was performed with 1/7- to 1/14-scale models of the ITV tee section.²⁻⁵ and instrumented epoxy models were tested to obtain K_I shape factors for surface flaws and stress concentration factors for nozzle corners. Tensile specimens 152-mm thick with surface flaws prototypic of ITV flaws were tested over a range of temperatures from lower shelf to upper shelf.⁶⁻⁹ Flawed tensile specimens scaled to match the small-scale steel vessels were tested. Information from the small-scale to full-scale tests was used to estimate the effect of section thickness on the "effective transition temperature" and to determine the effect of specimen size on apparent fracture toughness.

The experiments have been accompanied by several types of analyses.^{2-5,10,11} Structural analyses were made to define the elastic and elastic-plastic states of stress in the flawed region and to understand the influence of the vessel geometry on the stresses in this region. In view of the relative simplicity of analysis of unflawed structures, much of the fracture analysis was based upon superposition of

Table 8.1 Summary of test conditions for the Intermediate Vessel Test Program

Vessel	Test temperature (°C)	Material type	Toughness state	Flaw type ^b	Stress state	Loading ^b	Fracture mode
V-1	54	A508, Cl 2	Upper transition static upper shelf	Part circular outside surface	E&EP ^c	Pressure	Ductile tearing and mode conversion to cleavage
V-2	0	A508, Cl 2	Low transition	Part circular outside surface	E&EP	Pressure	Cleavage
V-3	54	Weld	Upper transition static upper shelf	Part circular outside surface	E&EP	Pressure	Ductile tearing and mode conversion to cleavage
V-4	24	Weld ^d A508, Cl 2	Low transition	Part circular outside surface (2 flaws)	E&EP	Pressure	Cleavage
V-5	88	A508, Cl 2	Dynamic upper shelf	Nozzle-corner notch	Stress concentration E&EP	Pressure	Ductile tearing; leak but no failure
V-6	88	A533, Gr B, Cl 1 Weld ^d	Dynamic upper shelf weld	Part circular surface flaws outside ^d (2) inside (1)	EP	Pressure	Ductile tearing and full shear tear
V-7	91	A533, Gr B, Cl 1	Dynamic upper shelf	Long, deep notch	EP	Pressure	Ductile tearing with leak but no failure
V-7A	88	A533, Gr B, Cl 1	Dynamic upper shelf	Long, deep notch	EP	Pressure, pneumatic, sustained load	Ductile tearing with leak but no failure
V-7B	87	HAZ ^e	Dynamic upper shelf	Long, deep notch	EP	Pressure, residual stress sustained load	Ductile tearing and leak with incipient tearing instability
V-8	-23	Weld	Low transition	Semielliptical outside surface	E	Pressure, residual stress ^f	Cleavage initiation and arrest (twice) with leakage but no failure
V-8A	157	Low-upper shelf weld	Dynamic upper shelf	Semielliptical outside surface	EP	Pressure	Stable and unstable ductile tearing terminated without leakage
V-9	24	A508, Cl 2	Low transition	Nozzle-corner notch ^g	Stress concentration EP&P	Pressure	Ductile tearing with mode conversion to cleavage
V-10 A ^g	>>RTNDT	A508, Cl 2	High transition	Shallow notch in nozzle corner	E	Cyclic pressure	Fatigue crack growth
B	<<RTNDT		Low transition	Nozzle corner notch	E	Pressure	Cleavage

^aInitial flaws in V-1 to V-9 were sharpened by fatigue or by EB welding (V-7 Series) and were oriented in a radial-axial plane.

^bMechanical loads were hydrostatic, except for V-7A, which was pneumatic.

^cE - elastic; EP - elastic-plastic.

^dFailure site.

^eHeat-affected zone of Section XI repair weld.

^fResidual stress from Section XI repair weld.

^gThis testing mode is not included in milestone schedule.

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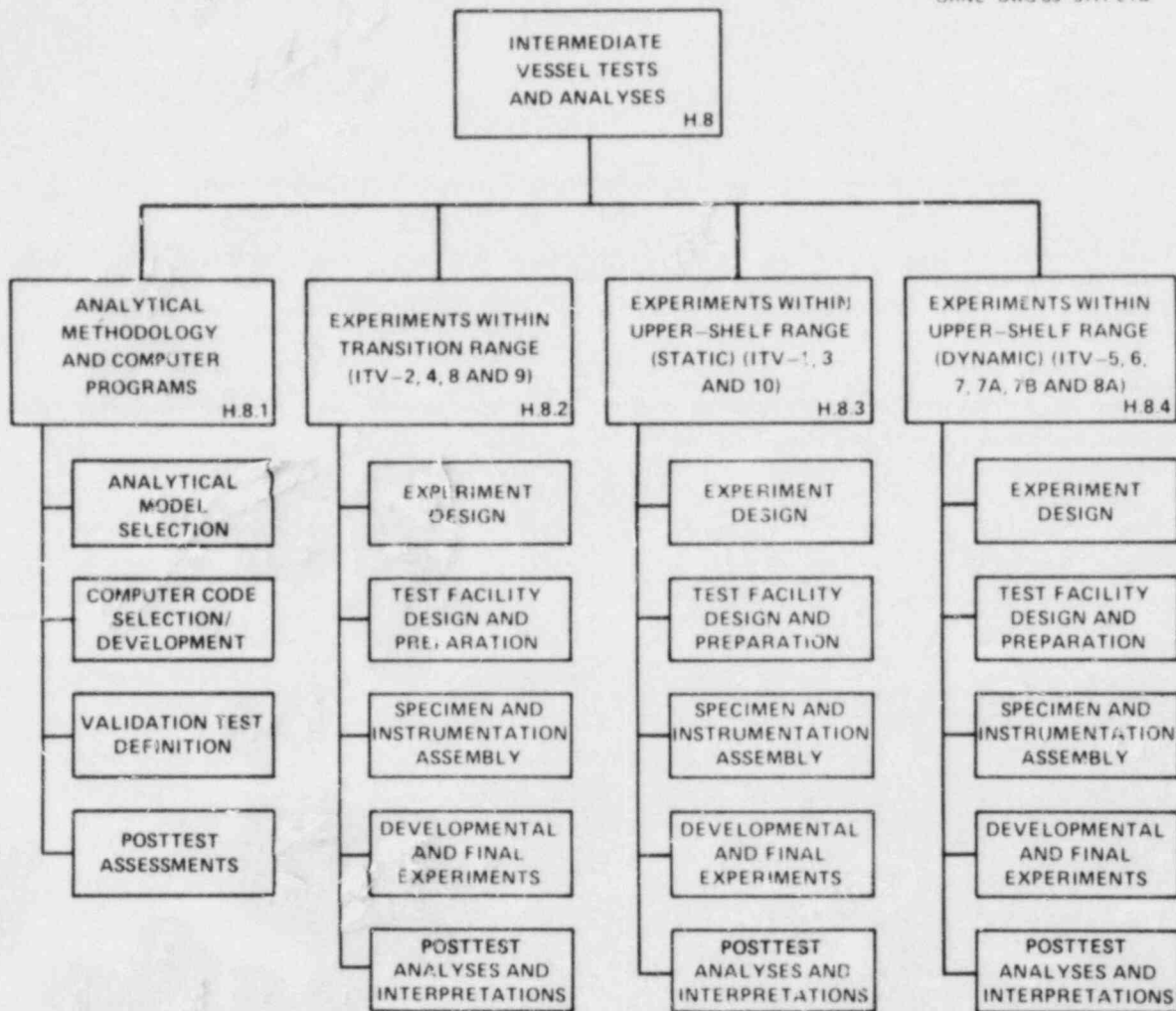


Fig. 8.1 Work breakdown structure for HSST Task H.8 Intermediate vessel tests and analyses.

stress fields of unflawed complex structures and simple flawed bodies. Models of failure that compete with fracture, such as tensile instability, were also investigated by analysis, since they are particularly important in cases in which flaws are large or toughness is high.

Every ITV test involves material properties determinations, generation of a flaw of desired geometry and acuity, pretest evaluation of flaw behavior and estimation of modes and conditions of fracture, and measurement during the test of the variables that define the state of stress of the vessel and geometry of the flaw. Twelve ITV tests have been performed successfully, so that methods of preparing and testing vessels have been well established. Four tests not originally planned have been conducted to study pneumatic pressurization (sustained loading), repair welds, residual stresses, low upper-shelf toughness, and tearing instability.¹¹⁻¹⁴ The demand for special test conditions and

more precise observation of flaw behavior will require continuing work to develop the techniques for future tests.

8.3 Plan of Action

Explicit preliminary plans have been made for testing the one untested vessel, V-10. A schedule is presented for a hypothetical fracture test of this vessel with a nozzle. This test would be performed well below the transition temperature and would be the first attempt to test the precise application of linear-elastic fracture mechanics (LEFM) to a flaw in a complex stress state. Earlier tests of vessels with nozzles were performed at such high temperatures that general yielding of the vessels preceded failure. A test under linear-elastic conditions is needed to show how LEFM should be applied to regions of stress concentration, a point on which earlier tests may have been interpreted by some people in an unconservative way.

Since V-10 is the last ITV with a nozzle, some consideration has been given to preceding the test described above, which will be a destructive test, by a fatigue crack growth test. This is shown in Table 8.1 as V-10A. Schedules and costs, however, are estimated only for the fracture test identified in the table as V-10B.

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8.5 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.8 are given in the following charts.

9. HSST TASK H.9 THERMAL-SHOCK TECHNOLOGY

9.1 Objective

The objectives of Task H.9 are to (1) investigate the behavior of inner-surface flaws in pressure vessels during severe thermal-shock loading conditions, and (2) evaluate severity of the pressurized thermal-shock problem to the extent necessary for defining an appropriate program for investigating flaw behavior.

9.2 Background

Thermal shock to PWR pressure vessels during postulated transients such as the large-break loss-of-coolant accident (LBLOCA) was identified as a possible challenge to vessel integrity as early as 1968. Preliminary studies conducted prior to 1973 indicated the possibility of crack initiation during a LBLOCA, but the ability of the crack to arrest could not be properly assessed because of a lack of appropriate crack-arrest toughness data. In 1973 the HSST staff recommended that a thorough study of the thermal-shock issue be undertaken, and that the effort should include, among other things, thermal-shock experiments designed to investigate the validity of the methods of analysis [primarily linear elastic fracture mechanics (LEFM)] as applied to thermal-shock loading conditions.

The HSST Thermal-Shock Task was established in 1973, and soon thereafter a finite-element method of analysis, based on linear-elastic fracture mechanics was developed for analyzing deep as well as shallow flaws. This tool was used to predict the behavior of two-dimensional flaws during LBLOCA loading conditions. Indications were that for the case of typically high-copper material and high fluence, very shallow flaws would initiate, and in a series of initiation-arrest events the flaw would penetrate deep into but not entirely through the wall. Furthermore, crack arrest had to take place with the stress intensity factor (K_I) increasing with crack depth, and in some cases warm prestressing, with K_I decreasing with time, could limit the depth to which the flaw would propagate.

It was decided that each of the above flaw behavior trends should be investigated experimentally under conditions similar to those expected for the PWR's. This required the use of thick-walled steel test cylinders, that would be flawed and thermally shocked on the inner surface, and the achievement of approximately the same potential for crack propagation as predicted for PWR vessels under LBLOCA thermal-shock loading conditions. Since the toughness of the test-cylinder material would not be reduced by radiation damage, as it is in a PWR vessel, it was necessary to use special heat treatments and/or a more severe thermal shock than expected for the PWR.

Eight thermal-shock experiments have been conducted thus far. The first four (TSE-1, -2, -3, -4) were relegated to an investigation of the behavior of shallow flaws and demonstrated initiation and arrest of long

and short shallow flaws in good agreement with LEFM. The remaining experiments (TSE-5, -5A, -6, -7) were conducted with larger diameter test cylinders so that deeper penetration of the flaw and other desired characteristics could be achieved. The results included demonstrations of multiple initiation-arrest events, deep penetration of the flaw, arrest in a rising K_I field, warm prestressing, large surface extension of short flaws, a lack of significant dynamic effects at arrest, and the inability of a flaw to completely penetrate the cylinder wall under thermal-shock loading conditions only. Each of these demonstrations validated the methods of analysis.

An important aspect of the experimental program is the determination of the fracture-toughness properties of the test-cylinder material, using small-size lab specimens, because in many cases the validity of LEFM is established on the bases of good agreement between lab toughness data and similar data deduced from the thermal-shock experiments. An important discovery in the process of obtaining the lab data was the existence of very large scatter in the crack initiation toughness. This has led to a reconsideration of the methods used to obtain valid data from a reasonable number of lab specimens and of the expected behavior of flaws in the test cylinders and PWR vessels. Task H.3 includes the characterization effort for TSE materials.

Another important part of the thermal-shock program has been the development of fracture-mechanics models and codes that are used for discovering the flaw behavior trends and that are subsequently used for sensitivity studies and assessing the severity of the OCA problem. Fracture-mechanics codes developed as a part of Task H.9 and which are still used extensively are FMECH, a two- and three-dimensional finite-element fracture-mechanics code; OCA-II, a fracture-mechanics code based on superposition techniques; and OCA-P, a probabilistics fracture-mechanics code that is a combination of OCA-II and a Monte Carlo routine.

Although the thermal-shock experiments have been devoted to the investigation of flaw behavior under thermal-shock-loading conditions only, a continuing analysis of OCA's has revealed the fact that the greatest challenge to vessel integrity comes from transients that involve high pressure as well as thermal shock. Pressure loading has little effect on the propagation of shallow flaws, but thermal-shock can drive the initially shallow flaw deep enough for pressure effects to be substantial. For some postulated OCA's the state-of-the-art methods of analysis indicate that following initiation of a shallow flaw there may be no arrest of the propagating flaw, the flaw finally penetrating the wall as a result of plastic instability (excessive pressure loading) in the remaining ligament. The actual behavior of the flaw under combined thermal and pressure loading is being examined experimentally as a part of Task H.10, along with assessments of predictive methods.

A summary of the experiments that have been conducted as a part of Task H.9 is presented in Table 9.1. References 1-2 are reports that have been prepared on completed tests. Reports on tests TSE-5, -5A, -6, and -7 are under preparation.

Table 9.1. Summary of thermal-shock experiments

Experiment identification	TSE-1	TSE-2	TSE-3	TSE-4	TSE-5	TSE-5A	TSE-6	TSE-7
Test cylinder								
Identification number	TSV-1	TSV-2	TSV-1	TSV-2	TSV-1	TSC-2	TSC-3	TSC-4
Dimensions, mm (in.)								
Inside diameter	242 (9.5)	242 (9.5)	242 (9.5)	242 (9.5)	686 (27)	686 (27)	838 (33)	686 (27)
Outside diameter	533 (21)	533 (21)	533 (21)	533 (21)	991 (39)	991 (39)	991 (39)	991 (39)
Length	914 (36)	914 (36)	914 (36)	914 (36)	1220 (48)	1220 (48)	1220 (48)	1220 (48)
Material	A508 class-2 chemistry							
Heat treatment	Quench only from 871°C (1600°F)				Tempered 613°C, 4 h	Tempered 679°C, 4 h	Tempered 613°C, 4 h	Tempered 704°C, 4 h
RTNDT, °C (°F)					66 (150)	10 (50)	66 (150)	-1 (30)
Flaw (initial)								
Orientation	Axial	Axial	Axial	Axial	Axial ^a Circumferential ^b	Axial	Axial	Axial
Length, mm (in.)	914 (36)	38 (1.50)	914 (36)	914 (36)	1220 (48) ^a ~6 (0.25)	1220 (48)	1220 (48)	38 (1.50)
Depth, mm (in.)	11 (0.42)	19 (0.75)	11 (0.42)	11 (0.42)	16 (0.63) ^{a,b}	11 (0.42)	7.6 (0.30)	~15 (0.60)
Generation Tech	Electron-beam weld							
Thermal shock								
Cylinder temperature (initial), °C (°F)	288 (550)	289 (552)	291 (555)	291 (555)	96 (205)	96 (205)	96 (205)	93 (200)
Sink temperature, °C (°F)	4 (40)	-23 (-10)	-23 (-10)	-25 (-13)	-196 (-320)	-196 (-320)	-196 (-320)	-196 (-320)
Quench medium	Water	Alcohol and water	Alcohol and water	Alcohol and water	LN ₂	LN ₂	LN ₂	LN ₂
Flaw behavior demonstrated	Non-initiation	Initiation-arrest w/moderate surface extension	Initiation-arrest	Initiation-arrest	Series of initiation-arrest events; negligible dynamic effects; extensive surface extension of short flaw	Series of initiation-arrest events; warm prestress; arrest in rising K _I field	Long crack jump w/neg. dynamic effects; arrest in rising K _I field; inability of flaw to penetrate wall	Extensive surface extension of short flaw

^aIntended flaw.^bInadvertent flaw.

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9.3 Plan of Action

The work breakdown structure for Task H.9 is shown in Fig. 9.1. The experimental efforts are organized by test and these are supported by a common analytical subtask.

Under combined thermal-shock and pressure loading conditions an initially shallow flaw will begin to propagate in the frangible (brittle) toughness regime and from then on will encounter increasingly tougher and higher temperature material as the crack moves radially through the wall at very high speed. At some point, presumably there will be a transition from frangible fracture to ductile tearing with a considerable reduction in crack speed and perhaps arrest of the crack. This particular combination of postulated events is referred to as arrest on the upper shelf, and it has not yet received much attention. In the fracture-mechanics analysis of OCA's it has generally been assumed that crack arrest will not take place if a crack arrest toughness greater than $\sim 200 \text{ MPa} \sqrt{\text{m}}$ is required. This may or may not be a reasonable approach.

Three experimental approaches are planned for investigating arrest on the upper shelf: experiments similar to the thermal-shock experiments with both thermal and pressure loading (Task H.10); wide-plate tests with a toughness gradient across the width of the plate (Task H.5); a thermal-shock experiment with the initial flaw located in a region having low Charpy energy at upper-shelf temperatures (low-upper-shelf material). This latter experiment, designated as TSE-8, is tentatively planned to be conducted in FY 1985 as a part of Task H.9.

PWR vessels are clad on the inner surface with an initially austenitic stainless steel material. Dilution with the base material and heat treating during application of the cladding leave the cladding material in an undetermined state with regard to fracture toughness and radiation-damage resistance. It is possible that the cladding resistance to crack propagation will be high enough to prevent surface extension of short flaws that extend through the cladding into the base material. If this is the case, and if it is reasonable to assume that initial flaws will not be long, it appears that failure of a PWR pressure vessel during an OCA will not be possible because a short flaw that cannot extend on the surface presumably cannot extend through the wall.

The effect of cladding on flaw behavior is being studied in Task H.7 using clad plates, and there are tentative plans for conducting thermal-shock experiments with clad cylinders as a part of Task H.9. Two experiments, TSE-9 and TSE-10 are scheduled for FY 1986 and 1987, respectively. Thermal-shock experiment TSE-7 demonstrated the ability of a short flaw to extend on the surface to become a very long flaw in the absence of cladding and serves as a base case for the series of experiments designed to reveal the effects of cladding.

Before the cladding-effects thermal-shock experiments can be conducted, it will be necessary to determine irradiation effects on the as-fabricated material. This is being done as a part of Task H.6.

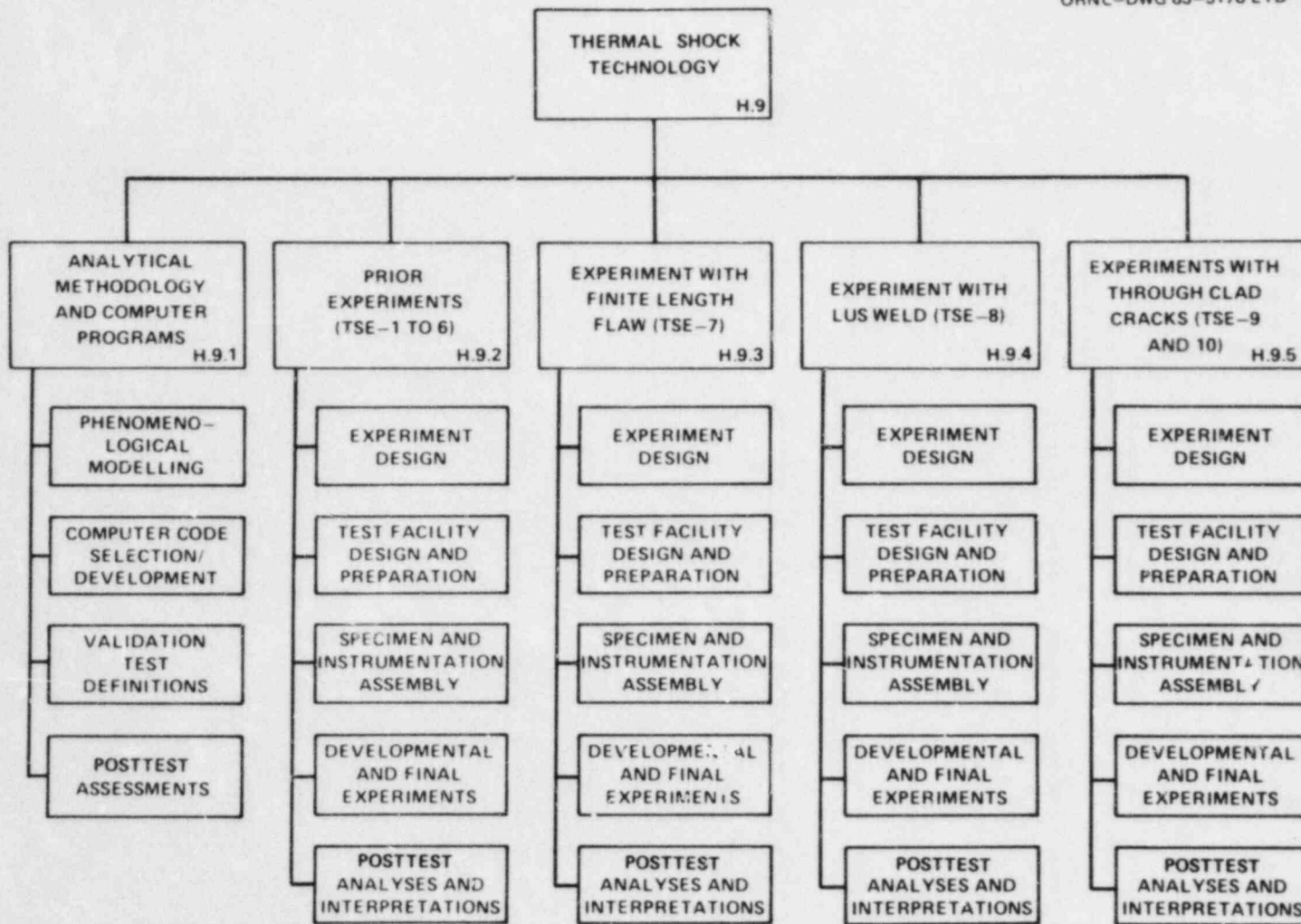


Fig. 9.1 Work breakdown structure for HSST Task H.9 Thermal Shock Technology.

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9.5 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.9 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.9 THERMAL SHOCK TECHNOLOGY

SUBTASK/MILESTONE	FY 83				FY 1984									FY 85				FY 86	FY 87	Beyond FY 87				
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
H.9.1 <u>Analytical Methodology and Computer Programs</u>																								
A. Issue Report on Modification to OCA-I to be Applicable to Clad Vessels			▲																					
B. Issue Report on OCA-II		▼	▼				▲																	
a. Incorporate finite flaw capability		▼																						
b. Complete qualification analyses			▼																					
C. Issue Report on (6/1, 2-m) Flaw Parametric Study										▲														
D. Issue Report on OCA-P and Coordinate with IPTS Studies		▼	▼							▲														
a. Select flaw probability model		▼																						
b. Complete qualification analyses			▼																					
E. Issue Report on Influence Coefficients											▲													
H.9.2 <u>Prior Experiments</u>																								
A. Issue Report on TSF-5, -5A, and -6																▲								

MILESTONE STATEMENT AND SCHEDULE

Task: H.9 THERMAL SHOCK TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87	
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
H.9.3 Experiment with Finite Length Flaw (TSE-7)																								
A. Complete Experiment Design		a	b	c																				
a. Identify characterization tests		▼																						
b. Complete characterization interpretation			▼																					
c. Complete pretest analyses				▼																				
B. Complete Test Facility and Test Cylinder Preparation		a	bc																					
a. Procure forging		▼																						
b. Complete system modifications			▼																					
c. Complete machining			▼																					
C. Complete Thermal-Hydraulic Test		a	b																					
a. Apply surface coating		▼																						
b. Complete instrumentation of test cylinder			▼																					
D. Complete Thermal-Shock Test and Issue Quick-Look Report			a-c																					
a. Generate flaw in Specimen			▼																					
b. Apply surface coating				▼																				
c. Complete instrumentation				▼																				

MILESTONE STATEMENT AND SCHEDULE

Task: H.9 THERMAL SHOCK TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984									FY 85				FY 86	FY 87	Beyond FY 87								
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1				2	3	4					
E. Issue Report on TSE-7				a					b																			
a. Complete posttest analyses																												
b. Complete interpretations and draft report																												
H.9.4 Experiment with LUS Weld (TSE-8)																												
A. Complete Experiment Design and Test Facility Preparation																												
a. Specify weld and cylinder configuration																												
b. Complete system modifications																												
c. Complete pretest analyses																												
B. Complete Fabrication of Test Cylinder																												
a. Complete fabrication of LUS weld insert (see Milestones H.3.1.E.a, H.5.3.C.a, and H.10.4.B.b)																												
b. Complete machining																												
c. Complete initial heat treatment																												
C. Complete Thermal-Hydraulic Test																												
a. Apply surface coating																												
b. Complete instrumentation of cylinder																												
c. Complete assembly & perform test																												

MILESTONE STATEMENT AND SCHEDULE

Task: H.9 THERMAL SHOCK TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984												FY 85				FY 86	FY 87	Beyond FY 87		
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
B. Issue Report on Test of Clad Specimen Containing 3-D Flaw and a Second Type of Cladding (TSE-10)																						a	b	c	
a. Complete experiment design																									
b. Complete thermal-hydraulic test																									
c. Complete thermal-shock test																									

10. HSST TASK H.10 PRESSURIZED THERMAL-SHOCK TECHNOLOGY

10.1 Objective

The objective of Task H.10 is to test and evaluate the fracture response of thick vessels under thermo-mechanical stress fields and with fracture characteristics realistic to overcooling accident conditions to (1) demonstrate flaw initiation and arrest behavior under frangible and non-frangible conditions, and (2) determine the applicability of theoretical methods of fracture mechanics.

10.2 Background

This task was undertaken to provide experimental data to validate analytical methods for assessing the response of reactor pressure vessels under conditions representative of an overcooling accident. Fracture analysis capabilities had been developed to this point on the basis of extensive fracture properties tests and on assessments of structural tests that had been performed in support of nuclear and non-nuclear technology development. Many of the developments in support of nuclear applications had been carried out by other tasks of the HSST program. Whereas Task H.8 and H.9 had provided data and assessments on the fracture behavior of pressurized vessels and thermally shocked cylinders separately, prototypical tests had not been performed under the combined thermal and pressure loadings. Therefore, preparations were initiated for tests and analytical assessments of the response of intermediate test vessels (ITV's) under combined loadings to validate the applicability of fracture methodology.

Efforts were initiated in FY 1982 to carry out specific experiments to investigate the initiation, growth, and arrest behavior a shallow crack in thermally-shocked pressurized ITV's. Early feasibility studies revealed that experimental practicalities suggested that the test vessel should be flawed and thermally shocked on the exterior. As far as the technical objectives are concerned, this test configuration gives the same basis for methods validation as if the flaw and thermal shock were on the inside. In defining tests and in designing the test facility, several issues were to be addressed:

- (1) intervention of the ductile upper shelf in arrest of a cleavage fracture
- (2) effectiveness of a variety of types of warm prestressing, including marginal conditions and antiwarm prestressing
- (3) behavior of short flaws in vessels with and without cladding and in regions with toughness and K_I gradients
- (4) upper shelf tearing instability and
- (5) arrest in high positive K_I gradients

In FY 1983 a major effort was devoted to preparing the pressurized thermal-shock test facility (PTSTF) in Building K-702, the abandoned power house building at K-25 in Oak Ridge. The engineering firm (Rust

Engineering) completed the basic construction of the facility in May 1983 on schedule and within budget. The facility was then turned over to ORNL for integration with the other test preparations. Other major activities in preparation for the first test (PTSE-1) that were concurrently and subsequently pursued vigorously in FY 1983 included (1) fabrication of two vessels for use in the shakedown experiment (PTSE-0) and PTSE-1, (2) design and installation of the instrumentation for vessels to be used in PTSE-0 and PTSE-1, (3) design and fabrication of specimen installation fixturing at the PTSTF, (4) vessel ballast, (5) design and assemblage of data acquisition system, (6) integration of all test systems, (7) material properties tests, and (8) performance of pretest analysis for test histogram definition.

10.3 Plan of Action

Within this five-year program plan, a series of three PTS experiments is envisaged. Each test is to assess the fracture characteristics associated with a representative PWR material, configuration, and loading. The first test is to use a base RPV material, A533 Grade B class 1 steel; the second test is to employ a low-upper-shelf weldment, and the third test vessel is to be clad with a prototypical stainless steel cladding. The first test (PTSE-1) is scheduled for January 1984, the second for mid FY 1985, and the third for FY 1987. The objectives of these three tests have been generally defined as:

- (1) PTSE-1 is to investigate warm prestressing and anitwarm prestressing effects on cleavage initiation and to demonstrate the upper-shelf arrest of a crack initiated in cleavage.
- (2) PTSE-2 is to demonstrate the upper-shelf arrest of a cleavage crack in low-upper-shelf material.
- (3) PTSE-3 is to investigate the influence of stainless steel cladding on the initiation and growth of a short flaw.

The work breakdown structure for this task is shown in Fig. 10.1 and is centered around these three tests, their analyses, and the preparation of the required test facility. The principal criteria on which the test program is based are:

- (1) The tests will be designed to challenge the predictions of analytical methods that are applicable to full-scale reactor pressure vessels under combined loading.
- (2) The scale of the tests will be large enough to attain effectively full-scale restraint of the flawed region.
- (3) Material in the flawed region will be characterized by specimen tests prior to each vessel test.
- (4) Test conditions and materials will be selected to produce:
 - a. realistic RPV stress fields and gradients around the flaw (with general primary membrane stress intensities less than ASME Code allowables) and
 - b. realistic fracture-toughness conditions in the zone of action

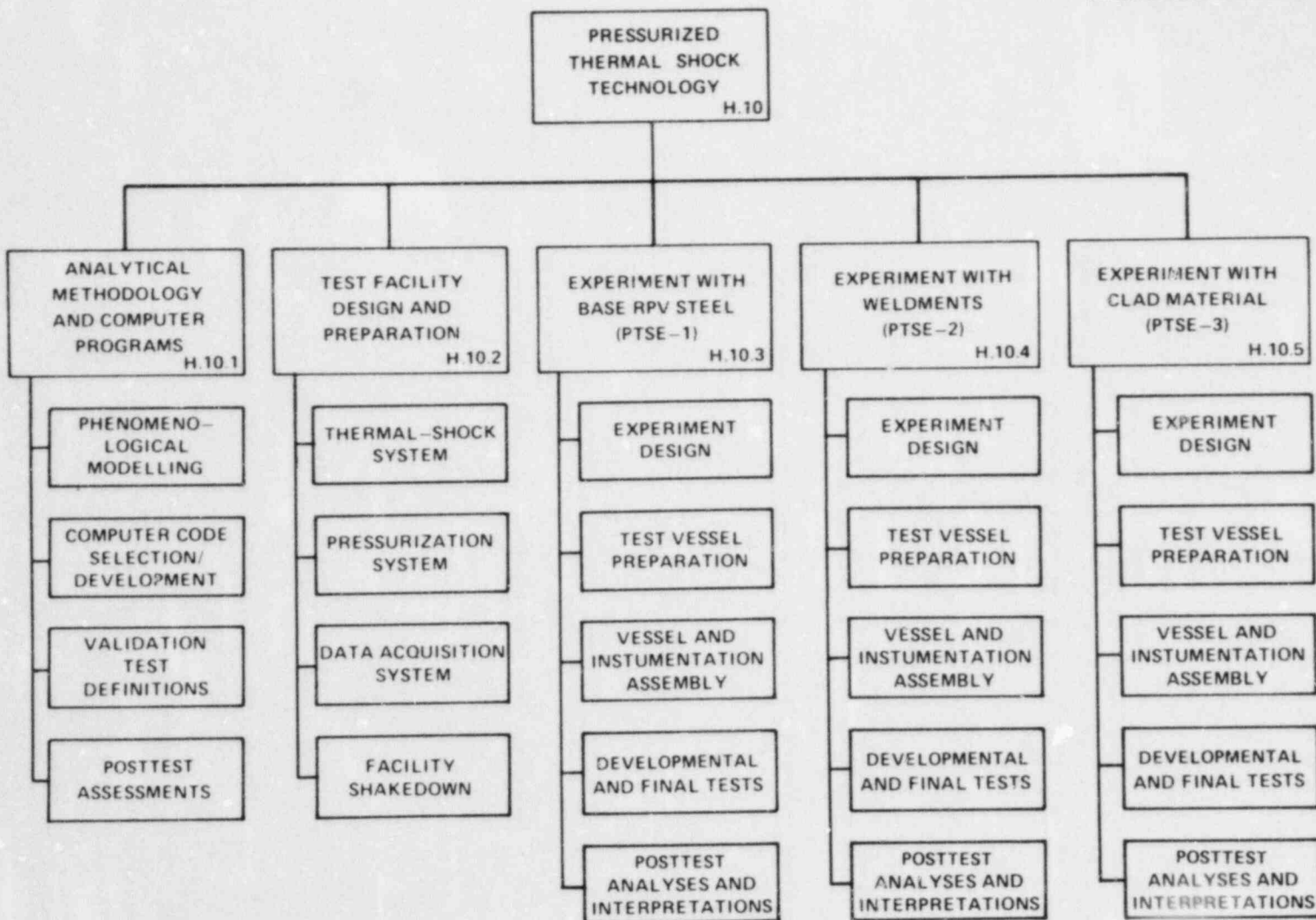


Fig. 10.1 Work breakdown structure for HSST Task H.10 Pressurized Thermal Shock Technology.

- (5) Loading conditions and controls will be used to prevent bursting the vessel (except when desired) to minimize damage to the test facility
- (6) The test facility will be capable of producing (with realistic stresses) a variety of fracture possibilities:
 - a. cleavage initiation of small flaws
 - b. cleavage initiation and arrest below the upper shelf
 - c. cleavage initiation with arrest on the upper shelf
 - d. arrest in a high positive K_I gradient
 - e. warm and nonwarm prestressing states in succession
 - f. progressive (upper-shelf) tearing, tearing instability, and restabilization

As noted in the Background section above, pressurized thermal-shock tests are an extension of the large-scale experimental fracture mechanics studies carried out as parts of the thermal-shock (H.9) and intermediate vessel test (H.8) tasks. A particularly important test condition attainable only in the PTS facility is the contemporaneous toughness gradient and flexible loading history. This capability makes it possible to consider simulating, in the neighborhood of a crack, both the toughness regimes and stress states that are obtained in severe hypothetical overcooling accidents. Furthermore, fracture phenomena of importance in evaluation of overcooling accidents (for example, antiwarm prestressing and upper-shelf arrest) can be investigated in thick sections only in the PTS experiments.

The specific test conditions for PTSE-2 and -3 will not be developed until information is available from other activities, including PTSE-1. TSE-8 (Task H.9) and wide-plate crack arrest tests (Task H.5) will be very relevant to defining PTSE-2. Results from the Seventh Irradiation Series studies from Task H.7 and TSE-9 and -10 (if performed) will be used in the definition of PTSE-3. Therefore, the details of these latter two tests are not considered specified at this time.

10.4 Milestone Statement and Schedule

The statement and schedule for the milestones in Task H.10 are given in the following charts.

MILESTONE STATEMENT AND SCHEDULE

Task: H.10 PRESSURIZED THERMAL SHOCK TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984								FY 85				FY 86	FY 87	Beyond FY 87						
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4					
B. Complete Test Vessel Preparation (continued)																									
b. Fabricate modified vessels			▼																						
c. Complete instrumentation of unflawed V-7 for prototype test PTSE-0				▼																					
d. Generate flaw in ITV-8							▼																		
e. Complete instrumentation of flawed V-8 for PTSE-1								▲																	
C. Complete Performance of PTSE-1																									
a. Complete prototype test of unflawed vessel (PTSE-0) to establish system parameters							▼																		
b. Complete test of flawed vessel (PTSE-1)													▼												
D. Complete Posttest Evaluations and Issue Report on PTSE-1																									
a. Complete data qualification and interpretation																									
b. Complete posttest fracture examinations																									
c. Complete fracture analyses and comparisons between predictions and data																									

MILESTONE STATEMENT AND SCHEDULE

Task: H.10 PRESSURIZED THERMAL SHOCK TECHNOLOGY (continued)

SUBTASK/MILESTONE	FY 83				FY 1984								FY 85				FY 86	FY 87	Beyond FY 87					
	1	2	3	4	O	N	D	J	F	M	A	M	J	J	A	S	1	2	3	4				
D. Complete Posttest Evaluations and Issue Report on PTSE-2																								
a. Complete data qualification and interpretation																								
b. Complete posttest fracture examinations																								
c. Complete fracture analyses and comparisons between predictions and data																								
H.10.F Experiment with Clad Material (PTSE-3)																								
A. Complete Design of PTSE-3 Using a Stainless Steel Clad Vessel																								
a. Establish test objectives																								
b. Specify test vessel materials																								
c. Establish experimental requirements																								
B. Complete Test Vessel Preparation																								
a. Design test vessel																								
b. Contract vessel cladding																								
c. Characterize material																								
d. ORNL receive clad vessel																								
e. Generate flaw in vessel																								

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NRC FORM 335 <small>(11-81)</small>		U. S. NUCLEAR REGULATORY COMMISSION BIBLIOGRAPHIC DATA SHEET		1. REPORT NUMBER (Assigned by DDC) NUREG/CR-3595 ORNL/TM-9008	
4. TITLE AND SUBTITLE (Add Volume No., if appropriate) Heavy-Section Steel Technology Program- Five-Year Plan FY 1983-1987				2. (Leave blank)	
7. AUTHOR(S) Staff				3. RECIPIENT'S ACCESSION NO.	
9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Oak Ridge National Laboratory P. O. Box X Oak Ridge, Tennessee 37830				5. DATE REPORT COMPLETED MONTH YEAR November 1983	
12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Division of Engineering Technology Office of Nuclear Regulatory Research U. S. Nuclear Regulatory Commission Washington, D. C. 20555				6. (Leave blank)	
				8. (Leave blank)	
				10. PROJECT/TASK/WORK UNIT NO.	
				11. FIN NO. B0119	
13. TYPE OF REPORT Program Plan			PERIOD COVERED (Inclusive dates)		
15. SUPPLEMENTARY NOTES				14. (Leave blank)	
16. ABSTRACT (200 words or less) <p>The first in an annual series of five-year program plan documents is presented for the Heavy-Section Steel Technology program. The program is carried out by the Oak Ridge National Laboratory for the Materials Engineering Branch, Division of Engineering Technology, Office of Nuclear Regulatory Research of the U. S. Nuclear Regulatory Commission. The program is aimed at advancing the understanding and validation of materials and structures behavior as they relate to light water reactor pressure vessel integrity. The program has nine technical tasks and a management function. A background statement and a plan-of-action is given for each. The nine technical tasks address fracture methodology and analysis, materials characterization, crack growth, crack arrest, irradiation effects, cladding evaluations, intermediate-vessel testing, thermal shock testing, and pressurized thermal-shock experiments.</p>					
17. KEY WORDS AND DOCUMENT ANALYSIS			17a. DESCRIPTORS		
Pressure vessels Ferritic steels Weldments Irradiation Cladding Flaws Thermal shock			Fracture mechanics Crack arrest Crack growth		
17b. IDENTIFIERS: OPEN-ENDED TERMS					
18. AVAILABILITY STATEMENT Unlimited			19. SECURITY CLASS (This report) Unclassified		21. NO. OF PAGES
			20. SECURITY CLASS (This page) Unclassified		22. PRICE \$

120555078877 1 1ANIRF
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