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Coordinated Irradiation Plan for the Fuel Refabrication and Development Program

J. O. Barner

April 1979

Prepared for the U.S. Department of Energy
under Contract EY-76-C-06-1830

Pacific Northwest Laboratory
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COORDINATED IRRADIATION PLAN FOR THE FUEL REFABRICATION AND DEVELOPMENT PROGRAM

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Richland, Washington 99352

SUMMARY

The Department of Energy's Fuel Refabrication and Development (FRAD) Program(1) is developing a number of proliferation-resistant fuel systems and forms for alternative use in nuclear reactors. A major portion of the program is the development of irradiation behavioral information for the fuel system/forms with the ultimate objective of qualifying the design for licensing and commercial utilization.

The nuclear fuel systems under development include denatured thoria-urania fuels and spiked urania-plutonia or thoria-plutonia fuels.

The fuel forms being considered include pellet fuel produced from mechanically mixed or coprecipitated feed materials, pellet fuel fabricated from partially calcined gel-derived or freeze-dried spheres (hybrid fuel) and packed-particle fuel produced from sintered gel-derived spheres (sphere-pac).

This document describes the coordinated development program that will be used to test and demonstrate the irradiation performance of alternative fuels.

The program relies upon the generation of data for key steady-state and safety-related phenomena, which have been identified for ultimate fuel performance modeling and licensing. The steady-state phenomena are:

- fission gas (product) release
- stored energy and fuel temperature distributions, and
- propensity for failure.

The safety-related phenomena are:

- reactivity insertion accidents
- departure from nucleate boiling
- transient-over-power, and
- the loss-of-coolant accident (LOCA).

Demonstration irradiations will be accomplished concurrently with the behavioral testing to permit correlation between the key behavioral characteristics of the alternative fuels and the existing, extensive data base for urania during both normal and safety-related operation.

This report provides general fuel designs, desired irradiation conditions, and preliminary test matrices, and schedules.

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INTRODUCTION

Several combinations of proliferation-resistant fuel systems and forms, hereafter called system/forms, are under development by the Department of Energy's Fuels Refabrication and Development (FRAD) Program.(1) The ultimate objective of the program is to produce licensable proliferation-resistant fuels for use in nuclear reactors.

A nuclear fuel system under consideration is thoria-urania that has been denatured (the fissile uranium content is less than 20% of the total uranium content). Other systems include the fuels urania- and thoria-plutonia that have been "spiked" to make the fuel highly radioactive.

The fuel forms being considered include pellets made from material that has been mechanically mixed or coprecipitated; a hybrid type of pellet made from partially calcined, gel-derived or freeze-dried spheres; and fuel consisting of spherical particles produced by the sol-gel process and packed to a high density (sphere-pac).

A coordinated irradiation program has been recommended to provide the operational data for the performance predictions and verifications required for commercial licensing of reload quantities of one or more of the alternative fuel types. The coordinated program would include not only management of the various types of irradiations, but, more importantly, provide comparative irradiations of all the system/forms under conditions that are as nearly identical as possible. This type of coordinated program will allow direct comparison of test results of each fuel system/form; such a comparison could not be made if each fuel fabricator individually tested the fuels that he produced. Another benefit of the program is a probable cost savings because fewer irradiations will be required.

Many years of research, testing and commercial operation have resulted in an extensive data base for urania during both normal and safety-related operation. The behavior of the thoria-urania, urania-plutonia and thoria-plutonia fuel systems, especially in the pelletized forms, is expected to be similar to the behavior of urania. Therefore, it is reasonable to develop an irradiation plan that identifies key behavioral characteristics for the alternative fuels to tie the results of these irradiations to the urania data base. From the results of these irradiations, performance predictions for the alternative fuels can be based upon a "normalized" urania data base. Verification demonstration irradiations will be used to confirm and/or modify the "normalized" performance prediction data base. A minimum number of fuel system/form variables and fuel physical parameters can be evaluated in such demonstration irradiations.

In order to provide the required information for the commercial licensing of one or more of the alternative fuels, an irradiation development program will be required that consists of 1) normal steady-state testing, including tests under off-normal conditions up to the limit of the plant protective system, 2) propensity-for-cladding-failure testing, 3) lead-rod demonstration irradiations, 4) lead-assembly irradiations, and 5) safety-related testing. Overall program scope, priorities, and monetary resources will influence the actual alternative fuels development. This initial version is intended to show the scope of an irradiation program that best meets the requirements to license alternative fuels(s) for commercial LWR utilization.

DEVELOPMENT PHILOSOPHY

The ultimate objective of any program to develop a new fuel, or fuel rod design, for commercial use is to qualify the design for licensing. Over the years, the data base of normal steady-state(a) performance for a new fuel type, e.g., pelletized urania, has developed through a natural progression of events that usually include:

1) the design of a new fuel rod based upon anticipated behavior and reactor design considerations,
2) the accumulation of operational data on the new fuel rod design from experimental test-reactor irradiations,
3) the development of computational models for performance predictions based upon the test-reactor data, and
4) verification of the performance predictions by the sequential irradiation, in commercial reactors, of a few lead rods, a few lead assemblies, and finally, a partial core of the new fuel.

This type of sequential plan has worked well in the past.

Historically, the data base of safety-related performance has not been as logically developed. Often, following commercial utilization of the fuel, additional test-reactor experimentation has been needed to verify models developed from extrapolation of steady-state behavioral data and out-of-reactor measurements. Knowledge of concerns for safety-related performance in current LWRs should permit a logical development sequence for new fuels that is similar to that for steady-state development.

For the near-term utilization of alternative fuels, one or more of the fuel system/forms could be substituted for those in existing LWR fuel assemblies. There is an extensive data base for normal and safety-related operation for urania in LWRs. It is anticipated that the behavior of the alternative fuel systems, especially the pelletized forms, will be similar to the behavior of urania.

(a) It is recognized that reactors do not operate at "steady-state." The term steady-state is used to differentiate between normal and off-normal operation and conceivable safety-related incidents.

Therefore, an irradiation plan for development of an alternative fuel could be abbreviated, as below, in comparison to the generic, normal steady-state and safety-related development sequences. Specifically, the plan (as Figure 1 illustrates) would:

1) utilize the extensive technical data base for urania, as modified by the addition of data on alternative fuel properties and behavior, for initial performance predictions,
2) spot check key steady-state behavioral phenomena on viable alternative system/forms in test reactors to provide "tie-points" to the urania data base,
3) spot check key safety-related behavioral phenomena on viable alternative fuel system/forms in test reactors to provide "tie-points" to the urania data base,
4) initiate, as early as possible, steady-state verification irradiations of viable alternative fuel system/forms in lead-rod demonstrations in commercial reactors, and finally,
5) irradiate lead-assembly demonstrations for the most promising alternative fuel system/form(s), as determined by the above testing and lead-rod irradiations and the proliferation-resistance goals of the program, in commercial reactors.

The recommended irradiation plan will provide adequate data for the design bases. The bases are necessary to make performance predictions that are required for the licensing of reload quantities of the alternative commercial reactor fuel system/form(s). The comparative behavioral information from the coordinated program will be free from biases that might otherwise occur because of differences in in-reactor operating conditions and/or characteristics of individual testing or demonstration reactors. The coordinated testing and demonstration program will have the following attributes:

1) a common experimental design for each phase of testing or demonstration, e.g., similar operating conditions, same reactor, similar burnup history, etc.,

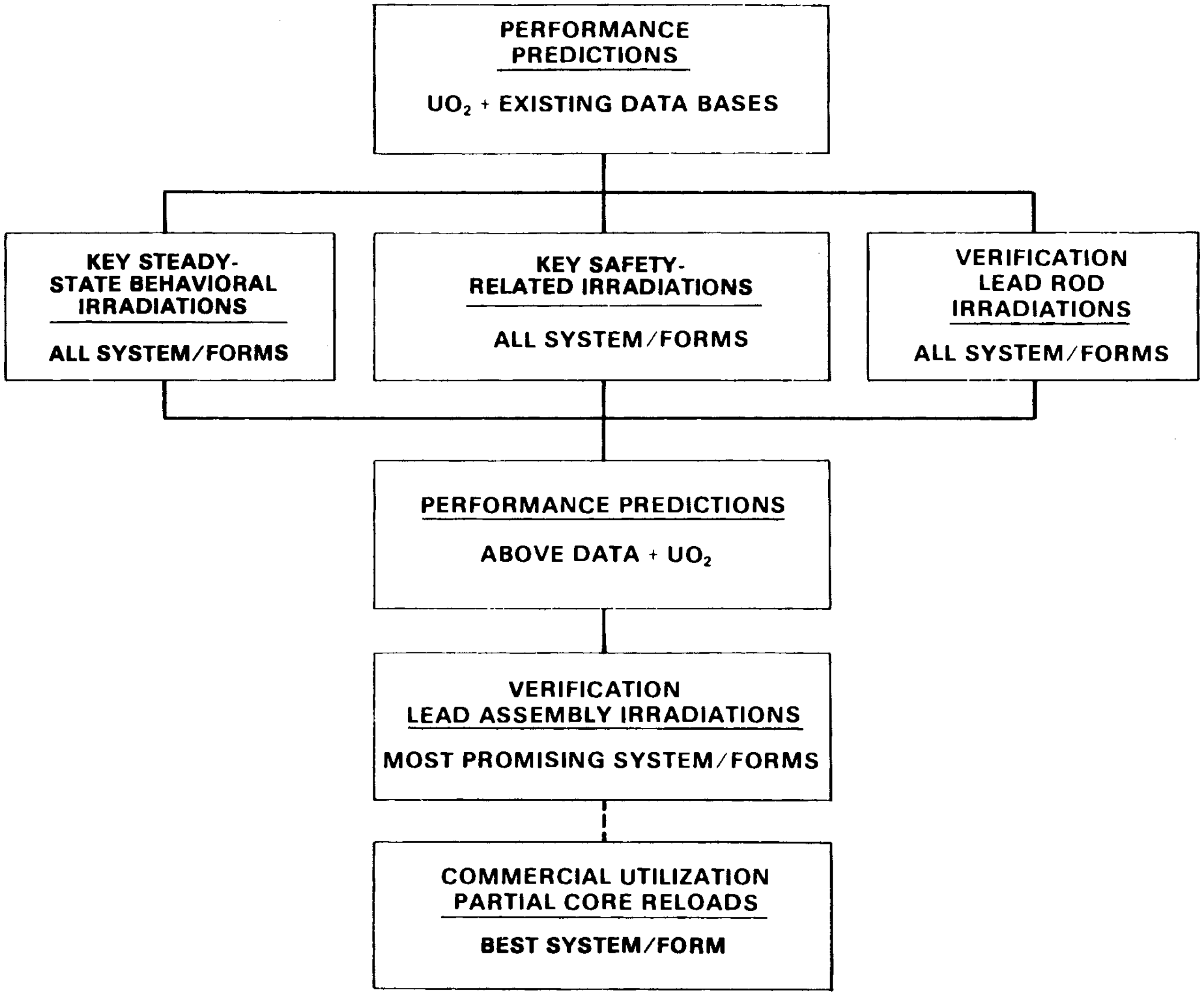


FIGURE 1. Alternative Fuels Irradiation Development Plan

2) a common fuel rod design for each phase of testing or demonstration for each system/form, e.g., same cladding materials, same geometric characteristics, same amount of pressurization, and

3) fuel rods produced by the appropriate fabricators, e.g., national laboratories for initial low-quantity testing and commercial fuel fabricators for large-quantity demonstrations.

A single fuel type, of a particular composition, porosity size and distribution, grain size and distribution, impurity level, density, etc., will be evaluated for each alternative fuel system/form. The selection of this fuel will be based upon its anticipated in-reactor behavior and similarity to existing urania fuel types. Fabrication capabilities and engineering judgment will also be major factors influencing selection.

A reference urania fuel design appropriate for each fuel system/form will be irradiated with the alternative fuel designs during all phases of testing and demonstration except the lead assembly irradiations. Appropriate data for both PWR and BWR fuel rod designs will be obtained during the steady-state key phenomena testing phase. Both PWR and BWR designs will be irradiated during the demonstration phases. Appropriate operating conditions will be determined during the safety-related key phenomena studies.

KEY STEADY-STATE PHENOMENA

The spot-check, key *steady-state* irradiations will provide information on critical behavioral phenomena. This data, in correlation with that on urania performance, will then form an information base for the ultimate licensing of alternative fuels for commercial reactor utilization. The selected critical phenomena are:

1) fission gas (product) release,
2) stored energy and fuel temperature distributions, and
3) propensity for failure.

Fission gas release during normal operation is an important behavioral phenomenon because it affects: 1) the internal fuel rod pressure and resultant stresses in the fuel rod cladding, 2) the fill gas conductivity, gap conductance, and thus, fuel operation temperatures and stored energy, and 3) the availability or transport of deleterious fission products for cladding corrosion and/or stress-corrosion cracking. Fission gas release will be measured on prototypic rods after operation at a minimum of at least two power levels as a function of burnup, i.e., values typical of the peak and core-average conditions.

Knowledge of stored energy and fuel temperature distributions during normal operation is important in defining the starting point for areas of concern during abnormal operation, e.g., the margin of operating temperature up to the point at which the fuel will melt during a transient overpower (TOP). Fuel temperature also affects such characteristics as fuel stability, restructuring, swelling and thermal expansion. Fuel temperature measurements will be conducted on prototypic rods at a minimum of two power levels as a function of burnup.

Propensity for rod failure during normal operation is of concern because it affects both total-reactor and local-assembly power maneuvering schemes. A high degree of stress, strain, or probability for rod failure can seriously restrict power shifts and assembly shuffling. Power-ramp testing on irradiated rods will be used to study the propensity for failure of the alternative fuels.

The results from the spot-check, key steady-state irradiations will be incorporated with property data generated from out-of-reactor measurements to modify or normalize steady-state behavioral models for urania that predict operating characteristics of fuel rods.

KEY SAFETY-RELATED PHENOMENA

The spot-check, key *safety-related* irradiations will also provide information on critical behavioral phenomena. This information, when correlated with data on urania performance, can provide a base of information for the licensing of alternative fuels. The key phenomena fall into four categories of fuel rod operation:

1) reactivity insertion accidents (RIAs),

2) departure from nucleate boiling (DNB), of which the power-cooling mismatch is a subcategory,

3) transient overpower, e.g., the anticipated transient without scram (ATWS), and

4) the loss-of-coolant accident (LOCA).

The phenomena are listed in the approximate order of their importance in the substitution of an alternative fuel for urania.

The differences in thermal conductivity and melting temperature between urania and alternative fuels are of concern during RIAs, e.g., higher stored energy and higher fuel temperatures before melting can be expected in thoria-urania fuel. At least three energy deposition ranges should be covered in order to correlate the behavior of urania and alternate fuels. Fresh, unirradiated fuel rods can be used for these tests.

During DNB, cladding temperatures increase above normal levels. Any significant differences in the rate of internal oxidation of the cladding between urania and alternate fuels are of concern, particularly if fuel rods are to be requalified for continued operation. Fission gas release during temperature transients also must be investigated. One or two tests at power/cooling mismatch conditions should be sufficient to provide a correlation with the urania performance data base. Both fresh and irradiated rods will be tested. For appropriate comparisons, the tests should be similar to previous tests on urania fuel.

During a mild ATWS, safety-related concerns would be minimal unless the number of failed alternative fuel rods was significantly larger than failed urania fuel rods. Rods experiencing mild overpower transients could be requalified for continued operation. Therefore transient fission gas release must also be measured and correlated with urania data. Anticipated transient without SCRAM testing will be combined with the propensity-for-failure power-ramp testing in order to reduce the total number of tests.

It must be demonstrated that internal and external cladding oxidation will be at an acceptable level during a LOCA. Unless the cladding oxidation behavior for alternative fuels is deleterious, single tests on unirradiated and irradiated rods should be sufficient to correlate alternative fuels and urania data bases.

FUEL DESIGNS

The proliferation-resistant fuel system/forms under study for LWR utilization include combinations of thoria, and/or urania and/or plutonia in pelletized and sphere-pac forms. Table 1 illustrates some of the possible fuel system/forms, including variations reflecting fabrication scheme-(mechanically mixed or coprecipitated feed), utilization schemes (denatured uranium for general use or highly enriched uranium or plutonium for use in a protected facility), and physical characteristics of the fuel (density, grain size, porosity distribution, chemical contaminants, etc.). It is not practical, and probably not possible, to test and/or demonstrate all the variations of the fuel system/forms listed in Table 1. Because fuel cycle studies and methods of obtaining proliferation-resistant systems are currently being studied, it is not possible at this time to prioritize the system/forms under consideration. The selection process must, of necessity, be somewhat arbitrary. However, as a first cut at selection, the tests should probably include at least one of each of the generic types listed. The following discussion attempts to provide a basis for the selection of the specific types to be included in the irradiations, at least initially.

Fuel forms under development consideration are the standard pelletized fuel, sphere-pac fuel, and a hybrid fuel consisting of pellets that are prepared from gel-derived, partially calcined spheres or from spheres produced by freeze drying. An advantage of using the standard pelletized form is many years of satisfactory industrial experience with this kind of fuel. Disadvantages, from a remote fabrication standpoint, are that it is a semi-batch, rather than a continuous, process and several stages of its manufacturing process produce a fine dust; in a remote fabrication operation, this would cause severe accountability and maintenance problems. On the other hand, the sphere-pac or freeze dry process could be automated to an essentially dust-free, basically continuous process. The major disadvantage in using these processes is a lack of industrial experience. The hybrid fuel concept combines the advantages of both: the proven technology of pelletized fuel and the essentially dustless processing of sphere technology. All three of the fuel form concepts will be tested.

TABLE 1. Alternative Fuel System/Forms

Generic Fuel Type	Fuel Cycle(a)	Possible Variables
1. $(Th,U)O_2$ Pellet (denatured from powder feed)	DUTH, HEUTH	Mechanical mixing Coprecipation U-content Physical characteristics Dissolution additives
2. $(U,Pu)O_2$ Pellet (spiked)	UP-U	Mechanically mixed Coprecipation Pu content Physical characteristics Spikant content
3. $(Th,Pu)O_2$ Pellet (spiked)	PUTH	Mechanically mixed Coprecipation Pu content Physical characteristics Spikant content
4. Sphere-Pac Fuel	Any	$(Th,U)O_2$ $(U,Pu)O_2$ (spiked) $(Th,Pu)O_2$ (spiked) UO_2 (Ref.) Physical characteristics
5. Hybrid Fuel (pellets)	Any	$(Th,U)O_2$ $(U,Pu)O_2$ (spiked) $(Th,Pu)O_2$ (spiked) Physical characteristics
6. Reference UO_2 (pellets)	LEU, DU	Spikant in DU

(a) DUTH = denatured uranium-thorium cycle (20-30% U in Th, less than 20% ^{235}U in U).
HEUTH = highly enriched uranium-thorium cycle (2-4% ^{233}U in Th).
PU-U = urania-plutonia cycle (2-6% Pu in ^{238}U).
PUTH = thoria-plutonia cycle (2-6% Pu in ^{238}U).
LEU = low enrichment urania cycle (standard 2-4% ^{235}U in U).
DU = denatured urania cycle (2-6% ^{233}U in ^{238}U).

Secondary variables for the pelletized designs include the material flow during fabrication, i.e., coprecipitated or mechanically mixed feed material, and the addition of agents to aid dissolution of thoria-urania during reprocessing. A fabrication flowsheet based upon coprecipitation fuel materials would require handling of significant quantities of materials of low radioactivity, e.g., ThO_2, throughout the remote fabrication facility. Thus, costs and facility size would be increased. The disadvantages of coprecipitation could be offset if the low radioactivity portion of the material feed could be added and mechanically mixed with the highly radioactive portion just prior to pelletizing. A performance data base does not exist for comparing the behavior of mechanically mixed and coprecipitated alternate fuels. Therefore, both types of fuels should be included in the testing program. This variable does not warrant full coverage and will be investigated only in the thoria-urania system.

Studies to date on dissolution aids for thoria-urania fuel have not identified a beneficial additive. Irradiations of such a material composition could be included in the program when, and if, a dissolution aid is identified.

For the thoria-urania fuel, two fuel compositions are currently included in system studies. Because the uranium content of the two types of fuels is drastically different, 20-30% in denatured cycle and 2-4% in highly enriched cycle, both types should be included in the testing.

Even though a considerable amount of data exists for urania-plutonia fuels, none of the previous irradiations have included a spikant. Therefore, some urania-plutonia with a spikant should be tested and demonstrated.

Presumably the sphere-pac and hybrid fuel types can be made with any of the fuel compositions. Of the alternative fuel types listed, initial emphasis for fabrication is being placed upon denatured urania-thoria. Initial irradiations should use urania-thoria, sphere-pac fuel.

The following system/form(s) have resulted from the above logic, and will be initially tested and demonstrated (all compositions are approximate):

1) pelletized $(Th_{0.80}U_{0.20})O_2$, derived from mechanically mixed feed material;
2) pelletized $(Th_{0.97}U_{0.03})O_2$, derived from mechanically mixed feed material;

3) pelletized $(Th_{0.80}U_{0.20})O_2$, derived from coprecipitated feed material;

4) pelletized $(U_{0.97}Pu_{0.03})O_2$, derived from mechanically mixed feed material, spiked;

5) pelletized $(Th_{0.97}Pu_{0.03})O_2$, derived from mechanically mixed feed material, spiked;

6) sphere-pac $(Th_{0.80}U_{0.20})O_2$, derived from sol-gel feed material;

7) pelletized hybrid $(Th_{0.80}U_{0.20})O_2$, derived from partially calcined, gel-derived or freeze-dried feed material; and

8) pelletized UO_2 reference fuel that is derived from powder feed material.

For the proposed testing and demonstrations, ^{235}U will be substituted for the ^{233}U that would be required during a normal fuel cycle. The spiked plutonia systems will utilize, along with ^{235}U, prototypic plutonia concentrations with an adjusted fissile content, as required for testing purposes. For fuel cycle schemes that entrain some radioactive fission products or add a spikant to increase proliferation resistance, surrogate, non-radioactive spikants will be added to obtain the anticipated compositions.

An adequate number of segmented rods of each type will be included in the lead-rod demonstrations for the power-ramp propensity-for-failure tests.

The results of two Department of Energy sponsored programs designed to alleviate the effects of fuel-cladding interaction in current fuel rod designs should be available for partial inclusion in this program in the early 1980s.(2,3) Fuels included in the second generation key steady-state phenomena and lead-rod demonstration irradiations will reflect the results of the DOE studies, where applicable, or include some of the combinations that were deleted in the above discussion. Results from these programs will also be taken into consideration when determining the final makeup of the initial experimental loadings for the initial, critical steady-state tests in this program.

The safety-related key phenomena experiments will concentrate on generic results. Final combinations of the fuel system/forms for testing will depend in part upon initial results from the key steady-state phenomena tests. A representative list might include:

1) pelletized fuel $(Th_{0.80}U_{0.20})O_2$ that is derived from mechanically mixed feed material;

2) sphere-pac $(Th_{0.80}U_{0.20})O_2$, and

3) pelletized "reference" UO_2.

Fuel rods for key steady-state phenomena tests and lead-rod demonstrations, including segmented rods for propensity-for-failure and safety-related testing, will be manufactured by appropriate program participants. Preferably, fuel rods for the lead-assembly demonstrations will be fabricated by selected PWR and BWR fuel vendors who have the current reload contract for the selected demonstration reactors. Technology required for the fabrication of the lead-assembly demonstration rods by the appropriate vendor(s) would be provided by the program.

IRRADIATION CONDITIONS

As alternative fuel system/forms are developed, the test rods should be irradiated under conditions that are as prototypic as possible. This is one of the reasons for irradiating most of the demonstration rods in actual PWR and BWR commercial reactors. Irradiating rods in test reactors necessarily requires some compromises in operating conditions, either because of rod instrumentation or reactor characteristics. Experimental rods for test reactor phases of the program will be designed to make the test results as generic and prototypic as possible.

For the direct substitution of an alternate fuel system into existing LWRs, testing should compare the new fuel system's behavior to that of UO_2 at equivalent power output per assembly. If the same fuel rod diameters are to be used for new fuel, the comparison should be made at equivalent linear heat ratings, because the plant will be expected to produce the same amount of electrical power no matter what fuel is used. Therefore, comparisons between fuel systems that use parameters other than heat ratings are of little value. Some minor adjustments in the equivalent power criteria may be required due to differences in in-reactor conversion of new fissile isotopes, but, as a first approximation, the comparisons should be made at equivalent linear heat ratings. This criterion is most easily obtained for the demonstration irradiations. Some compromises can be expected in the test reactor experiments.

Fuel rod behavior at peak operating conditions often imposes performance limits upon fuel systems and is, therefore, an important condition for conducting development irradiations. Of equal importance are the conditions at which most of the core operates. Average rod linear heat ratings are on the order of half of the peak ratings. Testing and demonstrations will be accomplished at both conditions.

Achieving high burnup is important due to the recent interest in resource utilization. Because test reactor experimentation is costly, the majority of the steady-state phenomena tests will be conducted to intermediate burnup levels, e.g., 1700 GJ/kg (20,000 MWd/MTM) with a limited number to burnups of about 3000 GJ/kg (35,000 MWd/MTM). The lead-rod and lead-assembly demonstration rods will be designed to achieve burnup levels of 4300 GJ/kg (50,000 MWd/MTM) with some rods being removed for examination at lower levels.

The inclusion of rod instrumentation, e.g., thermocouples, pressure transducers and elongation sensors, may have an effect upon the measured test results in the key steady-state phenomena tests. "Control" rods with no instrumentation will be included, where possible, in these tests to differentiate any effects of the instrumentation.

Tables 2 and 3 list the nominal operating conditions for which the steady-state testing and demonstration irradiations will be designed. Because many of the safety-related tests for urania are currently being conducted, design conditions for safety-related alternative fuel tests cannot be provided now. The section on key safety-related phenomena suggests some general requirements. Actual test conditions will be determined based upon anticipated incident conditions and the urania test experience.

TABLE 2. Operating Conditions for Instrumented Key Steady-State Behavior Tests

Parameter	Value
Linear Heat Rating, kW/m (kW/ft)	
Peak Conditions	42-48 (13-14.5)
Average Conditions	23-30 (7-9)
Burnup, GJ/kg (MWd/MTM)	
Majority of Tests	1700 (20,000)
Peak Burnup Tests	3000 (35,000)
Coolant Temperature, °C(a)	240-310

(a) Depending upon the testing facility, coolant temperatures may differ from prototypic BWR or PWR conditions. Adjustments in average power output may be required to produce fuel temperatures more prototypic of a commercial reactor.

TABLE 3. Operating Conditions for Demonstration Irradiations

Parameter	Value	
	BWR	PWR
Linear Heat Rating, kW/m (kW/ft)		
Peak Condition	44 (13.5)	49 (15)
Average Condition	15-25 (4.5-17.5)	15-30 (4.5-9)
Burnup, GJ/kg (MWd/MTM)		
Design Peak Condition	4300 (50,000)	4300 (50,000)
Intermediate Examination Condition	2200 (25,000)	2200 (25,000)
Coolant Temperature, °C	260-290	300-330

IRRADIATION TEST MATRICES AND SCHEDULE

Based upon the foregoing discussion, the irradiation testing and demonstration phases (tasks) fall into seven categories. The categories are cross-referenced to the work breakdown structures described in Work Breakdown Structure section. The seven categories (tasks) are:

1) overall coordination and management (W.B.S. 882.1),
2) key steady-state behavior (W.B.S. 882.2),
3) propensity-for-failure testing (W.B.S. 882.3),
4) lead-rod demonstration (W.B.S. 882.4),
5) lead-assembly demonstration (W.B.S. 882.5),
6) key safety-related behavior testing (W.B.S. 882.6), and
7) overall evaluation and program results (W.B.S. 882.7).

The activities in the coordination task, Item 1, and overall evaluations task, Item 7, are fairly obvious. Preliminary planning for the key safety-related tests, Item 6, and the lead-assembly tests, Item 5, is premature, except, generally, 1) the safety-related tests will be similar to those that will have been completed for urania and, 2) it is planned to irradiate four lead PWR assemblies and eight lead BWR assemblies. The selected fuel for the lead assembly irradiations will be determined from the previous testing and demonstrations, proliferation resistance studies, and nuclear systems studies. Operating conditions will probably include one fourth of the assemblies, each at a high and a low power level, and half of the assemblies at an intermediate power level.

Preliminary test matrices for the earlier phases, i.e., the critical steady-state irradiations, Item 2, and the lead-rod demonstration irradiations, Item 4 (including segmented rods for the propensity-for-failure testing, Item 3), can possibly be recommended at this time. Because a test reactor has not been selected for the key steady-state tests, two possible matrices have been illustrated. The listed test reactors are the Halden Boiling Water Reactor (HBWR) at Halden, Norway and the R-2 at Studsvik, Sweden. Reference to these two reactors does not imply that they are the only possible facilities, but is only meant to illustrate the types of matrices that could be tested at each of the facilities. Tables 4 and 5 illustrate the preliminary HBWR and R-2 matrices for the key steady-state tests. In both cases the matrices have common features:

1) all seven alternative fuel system/forms are tested,
2) a reference pellet fuel is tested,
3) all rods have pressure transducers and several rods have centerline thermocouples, and
4) both high and low powers and high and intermediate burnups are included.

In the case of the HBWR tests, an intermediate power level that can be easily accommodated is included.

Removal of a portion of the rods at an intermediate burnup level is planned for either matrix. Replacement rods would probably include advanced designs which would utilize features from the improved concept programs currently being sponsored by DOE or other combinations of alternative fuel system/forms.

Table 6 gives a preliminary demonstration matrix for the PWR and BWR lead-rod irradiations.(Item 4). The alternative fuel system/forms and the reference fuel are included in the initial series. Operating conditions would be as listed in Table 3. Adequate segmented rods are provided for ramp testing and safety-related tests. The segmented rods will probably be composed of four or five rodlets of approximately equal length. A second series of demonstrations with advanced designs is included in the planning. This series is optional, depending upon previous results and program requirements determined at that time. Vendor/power company participation will be required for both the PWR and BWR lead-rod irradiations.

A preliminary schedule for the developmental irradiations is shown in Table 7. Rodlets for propensity-for-failure tests, 32-48 tests, and the safety-related tests will be irradiated, before testing, in the lead-rod demonstrations.

Postirradiation examination will be completed on the key steady-state and safety-related test rods and lead-rod demonstration rods. Not all will be thoroughly examined, however; rods selected for such examination will be made on the basis of the data previously generated for that rod or rod type.

TABLE 4. Possible Test Matrix, HBWR Key Steady-State Phenomena (W.B.S. 882.2)

FUEL SYSTEM	FUEL FORM[1]	RODS WITH BURNUP, POWER AND INSTRUMENTATION SHOWN[2]						NUMBER RODS
		INITIAL LOADING TEST P-1						
$(Th_{0.80}U_{0.20})O_2$	MM	H H T/P$_1$	H M P$_1$	M H T/P$_2$ *	M M P$_2$ *	M L T/P$_1$	L L P$_2$ *	6
$(Th_{0.97}U_{0.03})O_2$	MM	H H T/P$_2$	H M P$_2$	M L T/P$_2$				3
$(Th_{0.80}U_{0.20})O_2$	COPPT	H H T/P$_1$	H M P$_1$	M L P$_1$				3
$(Th_{0.80}U_{0.20})O_2$	HYBRID	H H T/P$_1$	H M P$_1$	M L P$_1$				3
$(Th_{0.80}U_{0.20})O_2$	SPHERE-PAC	H H T/P$_1$	M H T/P$_2$ *	H M P$_1$	M M P$_2$ *	M L T/P$_1$	L L P$_2$ *	6
$(U_{0.97}Pu_{0.03})O_2$	MM	H H T/P$_1$	M H T/P$_2$ *	H M P$_1$	M M P$_2$ *	M L P$_1$	L L P$_2$ *	6
$(Th_{0.97}Pu_{0.03})O_2$	MM	H H T/P$_1$	M H T/P$_2$ *	H M P$_1$	M M P$_2$ *	L L T/P$_2$	L L P$_2$ *	6
UO_2	REF	H H T/P$_2$	H M P$_2$	M L P$_1$				3
								TOTAL 36 RODS
		SECOND LOADING TEST P-2						
ADVANCED DESIGN NO. 1		M H P	M M P	L L P				3
ADVANCED DESIGN NO. 2		M H P	M M P	L L P				3
ADVANCED DESIGN NO. 3		M H P	M M P	L L P				3
UO_2 REF		M H P	M M P	L L P				3
								TOTAL 12 RODS
								GRAND TOTAL 48 RODS

BU LHR I

BURNUP:	HIGH	= 3000-3500 GJ/KG
	MODERATE	= 2000-2500 GJ/KG
	LOW	= 1500-1800 GJ/KG
LINEAR HEAT RATING:	HIGH	= 42-48 KW/M
	MODERATE	= 35-40 KW/M
	LOW	= 20-30 KW/M
INSTRUMENTATION:	T	= FUEL CENTERLINE THERMOCOUPLE
	P	= PRESSURE TRANSDUCER

*ROD REMOVED AFTER INITIAL OPERATION AND REPLACED WITH APPROPRIATE ROD IN SECOND LOADING

(1) MM = MECHANICALLY MIXED, COPPT = COPRECIPITATED

(2) SUBSCRIPT IS RIG NUMBER

TABLE 5. Possible Test Matrix, R-2 Key Steady-State Phenomena (W.B.S. 882.2)

FUEL SYSTEM	FUEL(1) FORM	RODS WITH BURNUP, POWER AND INSTRUMENTATION SHOWN(2)				NUMBER RODS
		INITIAL LOADING, TEST P-1				
$(Th_{0.75}U_{0.25})O_2$	MM	H H T/P$_1$	H H T/P$_2$ *	H H P$_3$	M L T/P$_6$	4
$(Th_{0.97}U_{0.03})O_2$	MM	H H T/P$_4$	H H P$_5$	M L T/P$_7$		3
$(Th_{0.75}U_{0.25})O_2$	COPPT	H H T/P$_4$	H H P$_5$	M L T/P$_7$		3
$(Th_{0.75}U_{0.25})O_2$	HYBRID	H H T/P$_4$	H H P$_5$	M L T/P$_7$		3
$(Th_{0.75}U_{0.25})O_2$	SPHERE-PAC	H H T/P$_1$	M H T/P$_2$ *	H H P$_3$	M L T/P$_6$	4
$(U_{0.97}Pu_{0.03})O_2$	MM	H H T/P$_1$	M H T/P$_2$ *	H H P$_3$	M L T/P$_6$	4
$(Th_{0.97}Pu_{0.03})O_2$	MM	H H T/P$_1$	M H T/P$_2$ *	H H P$_3$	M L T/P$_6$	4
UO_2	REF	H H T/P$_4$	H H P$_5$	M L T/P$_7$		3
						TOTAL 28 RODS
		SECOND LOADING, TEST P-2				
ADVANCED DESIGN NO. 1		M H T/P				1
ADVANCED DESIGN NO. 2		M A T/P				1
ADVANCED DESIGN NO. 3		M H T/P				1
UO_2 REF		M H T/P				1
						TOTAL 4 RODS
						GRAND TOTAL 32 RODS

BU LHR I

BURNUP: HIGH = 3000-3500 GJ/KG
MODERATE = 2000-2500 GJ/KG
LINEAR HEAT RATING: HIGH = 42-48 KW/M
MODERATE = 25-35 KW/M
INSTRUMENTATION: T = FUEL CENTERLINE THERMOCOUPLE
P = PRESSURE TRANSDUCER

* ROD REMOVED AFTER INITIAL OPERATION AND REPLACED WITH APPROPRIATE ROD IN SECOND LOADING

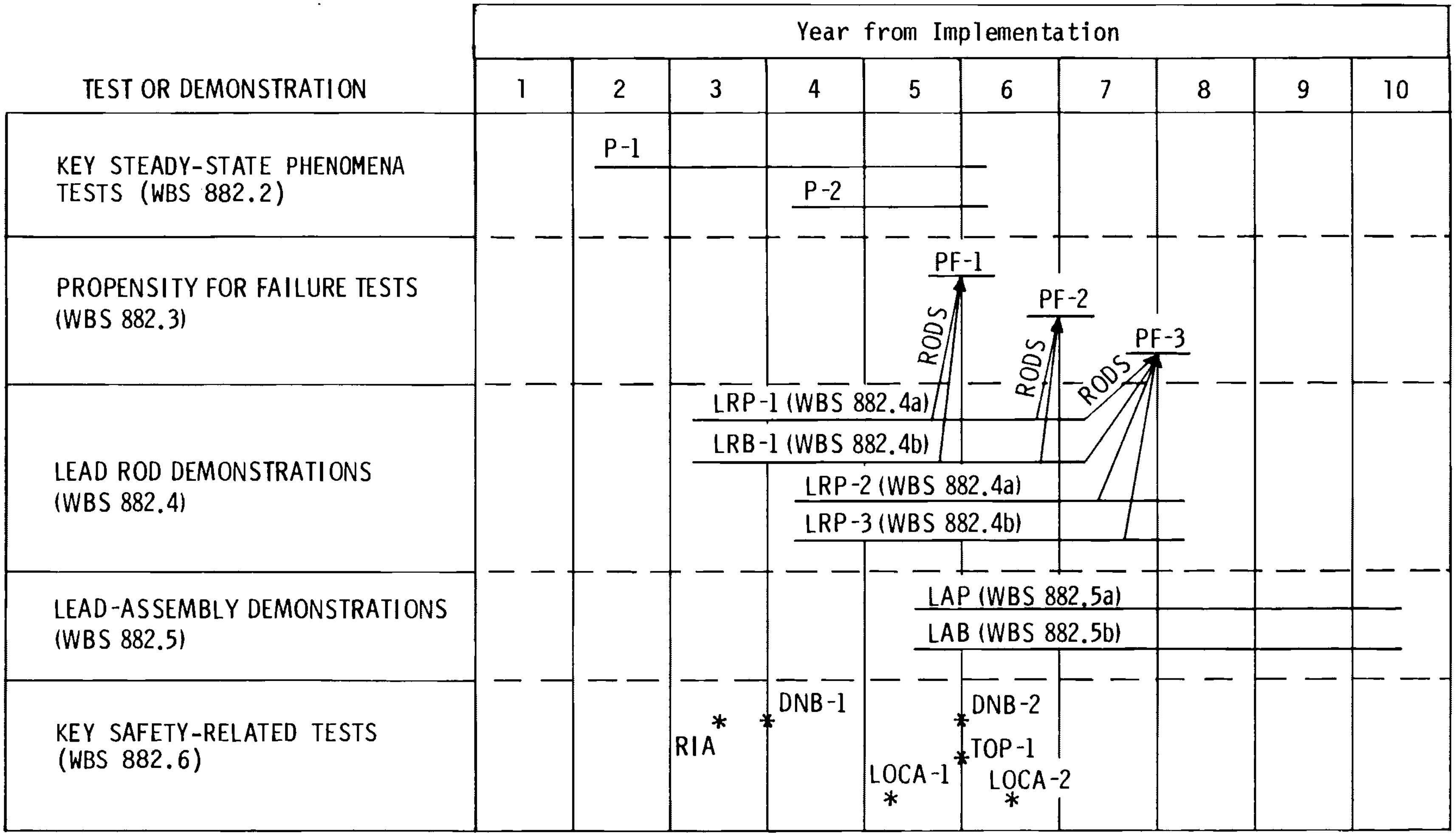
(1) MM = MECHANICALLY MIXED, COPPT = COPRECIPITATED

(2) SUBSCRIPT IS CAPSULE NUMBER

TABLE 6. Preliminary Demonstration Matrix Lead-Rod Irradiations (W.B.S. 882.4)

Fuel System	Fuel Form	PWR Rods (W.B.S. 882.4a)		BWR Rods (W.B.S. 882.4b)	
		No. Full-Length	No. Segmented (W.B.S. 882.4 and 882.6)	No. Full-Length	No. Segmented (W.B.S. 882.4 and 882.6
		Demonstration LRP-1		Demonstration LRB-1	
$(Th_{0.80}U_{0.20})O_2$	m.m.	15	5	15	5
$(Th_{0.97}U_{0.03})O_2$	m.m.	10	5	10	5
$(Th_{0.80}U_{0.20})O_2$	coppt.	10	5	10	5
$(Th_{0.80}U_{0.20})O_2$	hybrid	10	5	10	5
$(Th_{0.80}U_{0.20})O_2$	sphere-pac	15	5	15	5
$(U_{0.97}Pu_{0.03})O_2$	m.m.	15	5	15	5
$(Th_{0.97}Pu_{0.03})O_2$	m.m.	15	5	15	5
UO_2	ref.	10	5	10	5
Totals		100	40	100	40
		Demonstration LRP-2		Demonstration LRB-2	
Advanced Design 1		15	5	15	5
Advanced Design 2		15	5	15	5
Advanced Design 2		15	5	15	5
UO_2 Ref		5	5	5	5
Totals		50	20	50	20

TABLE 7. Preliminary Irradiation Schedule (W.B.S. 882)



SCREENING TESTS

The prior sections described the coordinated testing plan, including a generalized schedule. Because the date the plan will be implemented is uncertain, an adjunct series of screening irradiations was also planned. These tests, to be performed jointly with the Savannah River Laboratories (SRL), will provide comparative results relatively quickly for the different fuel system/forms. They will also provide irradiated material for dissolution studies at SRL. The tests will be conducted in an SRL production reactor for a period of approximately eight months. Peak linear heat ratings of 59 kW/m (18 kW/ft) were selected to partially offset the low coolant temperature in the SRL reactor, yet produce fuel temperatures approximating peak LWR fuel temperatures. Peak burnups in excess of 1700 GJ/kg (20,000 MWd/MTM) are expected. Both comparative general behavioral information and fission gas release data will be obtained from the tests. Using the general line of logic described previously, the following fuel types were selected for testing: (1) pelletized reference UO_2; (2) pelletized $(Th_{0.8}U_{0.2})O_2$; (3) sphere-pac $(Th_{0.8}U_{0.2})O_2$; (4) hybrid pelletized $(Th_{0.8}U_{0.2})O_2$ produced from calcined or freeze-dried microspheres; (5) pelletized $(Th_{0.8}U_{0.2})O_2$ produced with a dissolution aid, e.g., MgO; (6) pelletized $(Th_{0.98}Pu_{0.02})O_2$; and (7) pelletized ThO_2.

WORK BREAKDOWN STRUCTURE

The overall work breakdown structure for the testing and demonstration irradiation program is shown in Figure 2. Detailed work breakdown structures for each of the testing and demonstration tasks are shown in Figures 3 through 9. The earlier tasks are shown in the most detail. The charts will be updated as planning for the later phases becomes more detailed.

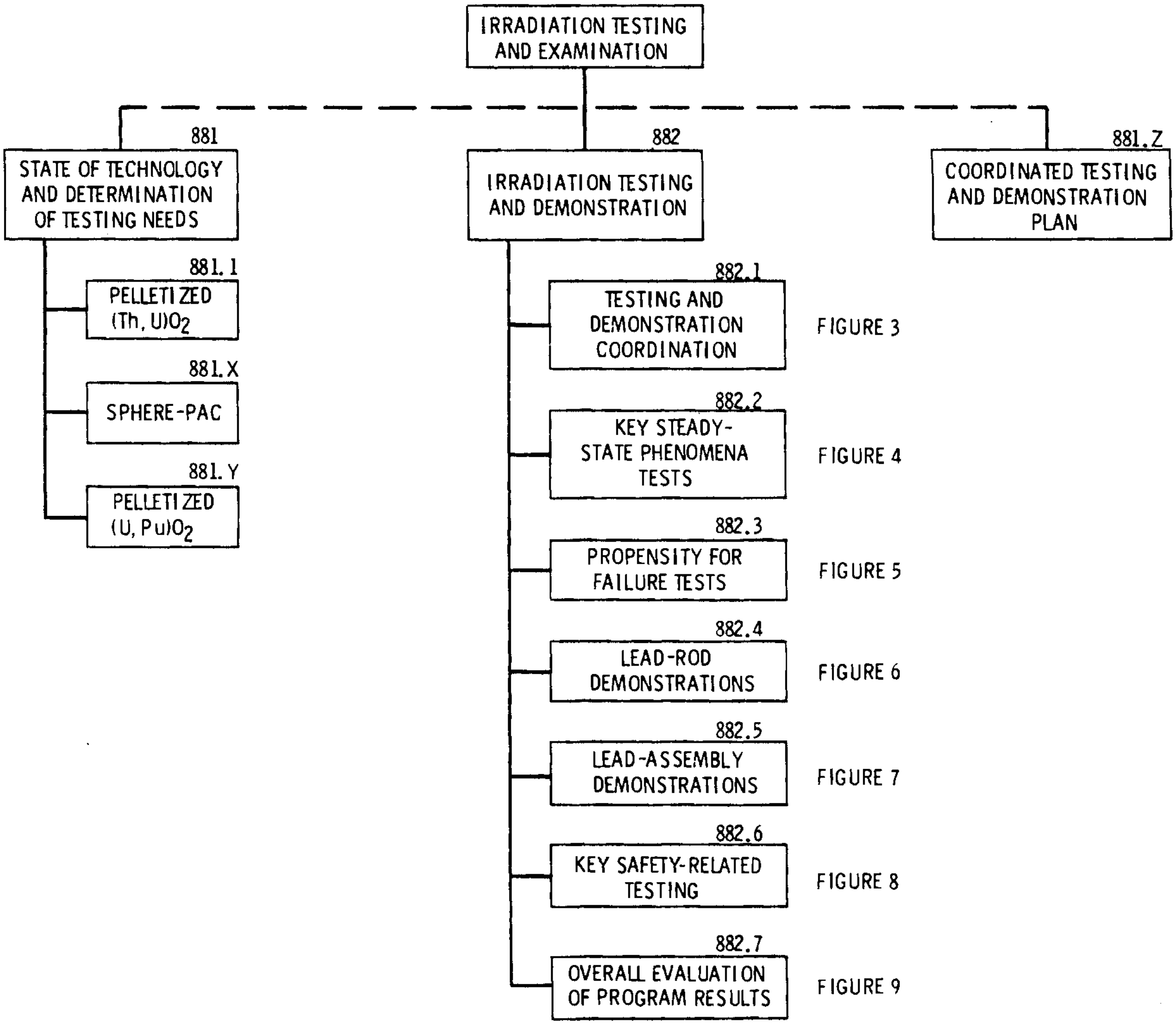


FIGURE 2. Overall FRAD Irradiation Testing and Demonstration Irradiation Plan

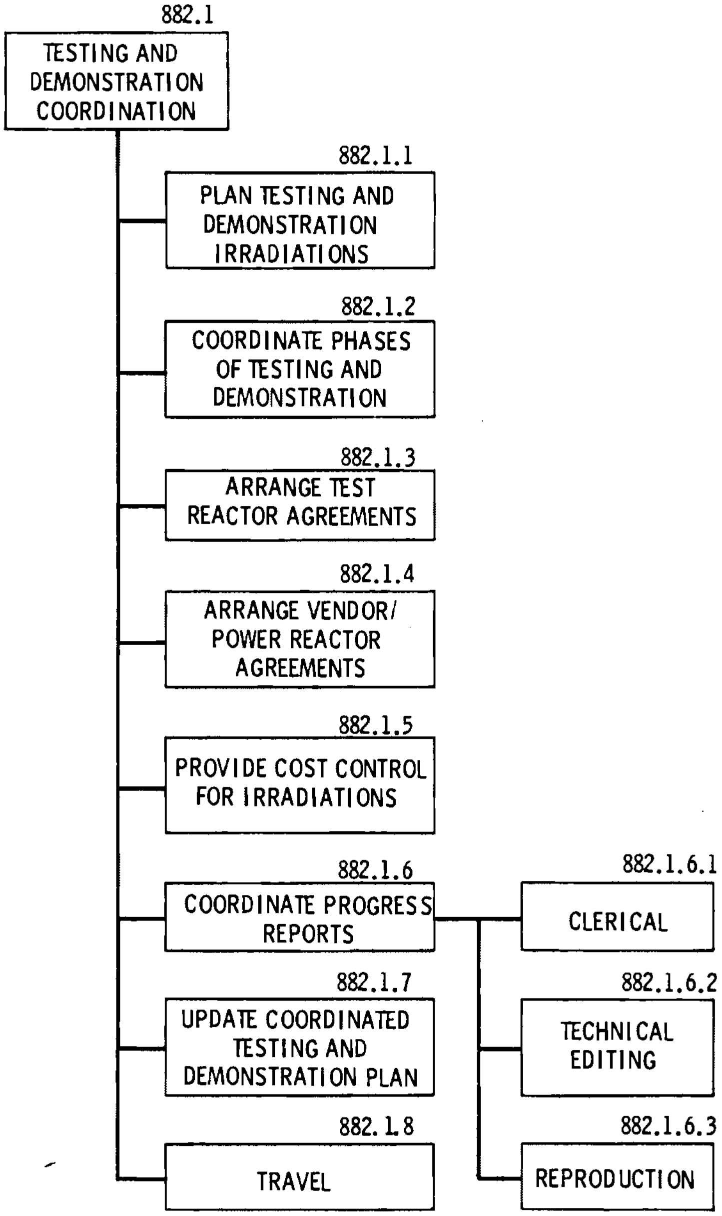


FIGURE 3. Work Breakdown Structure for FRAD Testing and Demonstration Coordination

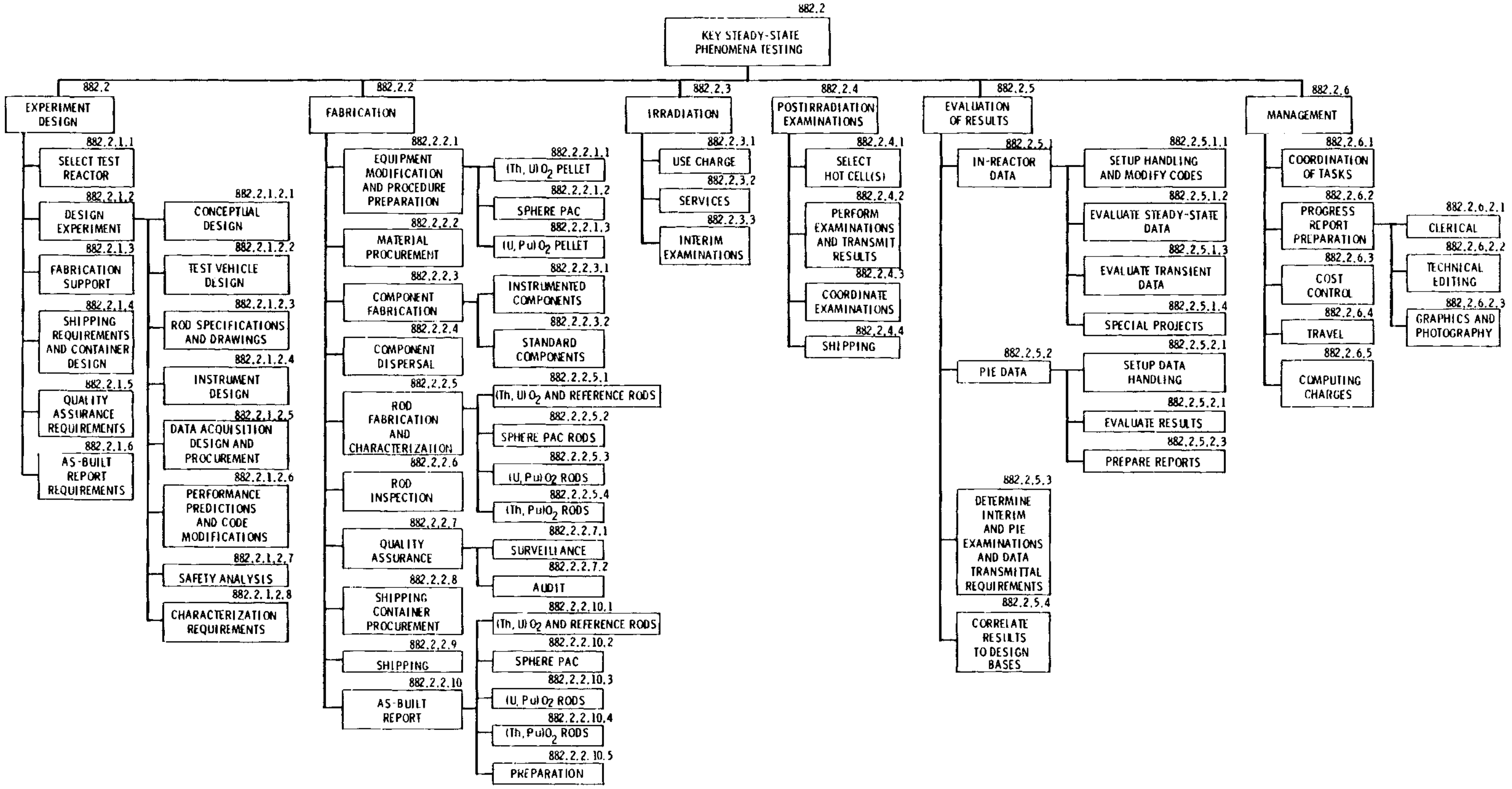


FIGURE 4. Work Breakdown Structure for FRAD Key Steady-State Phenomena Testing Activity

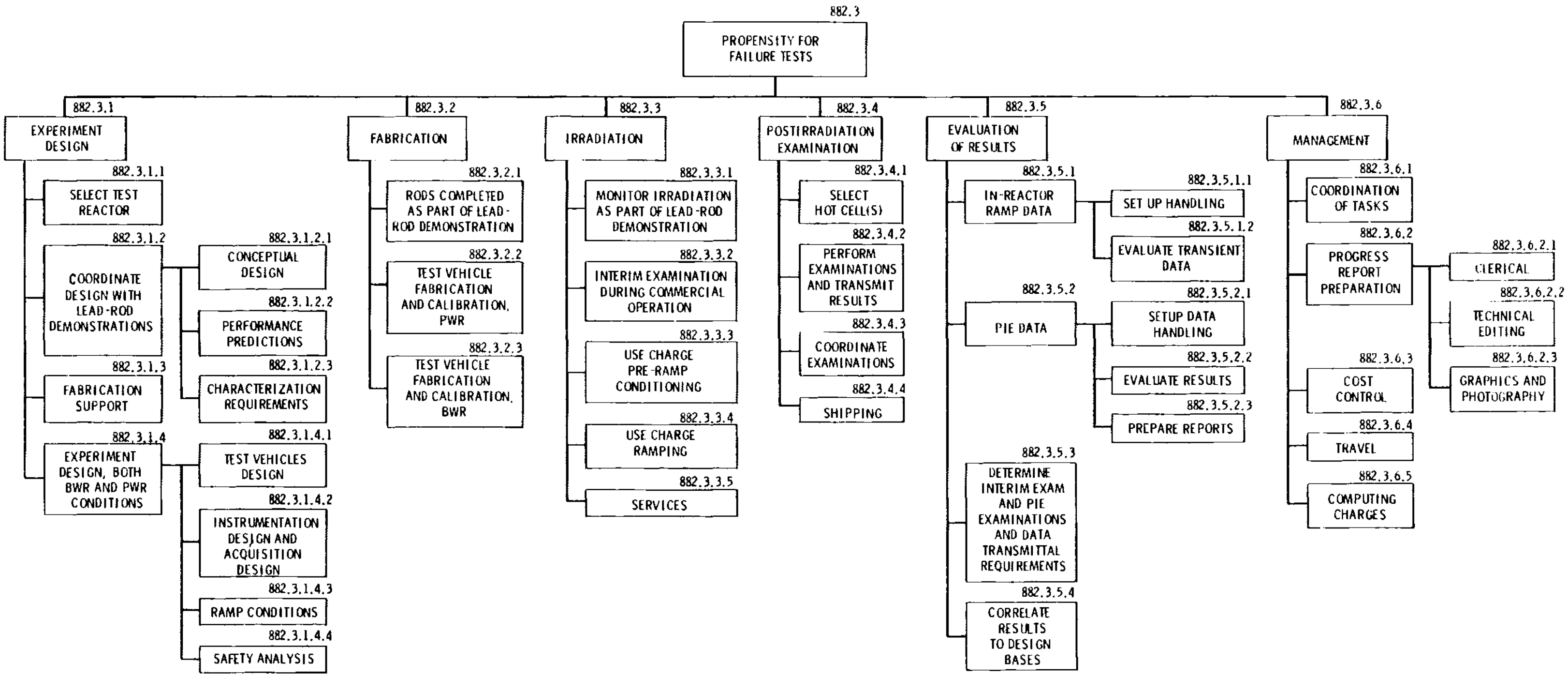
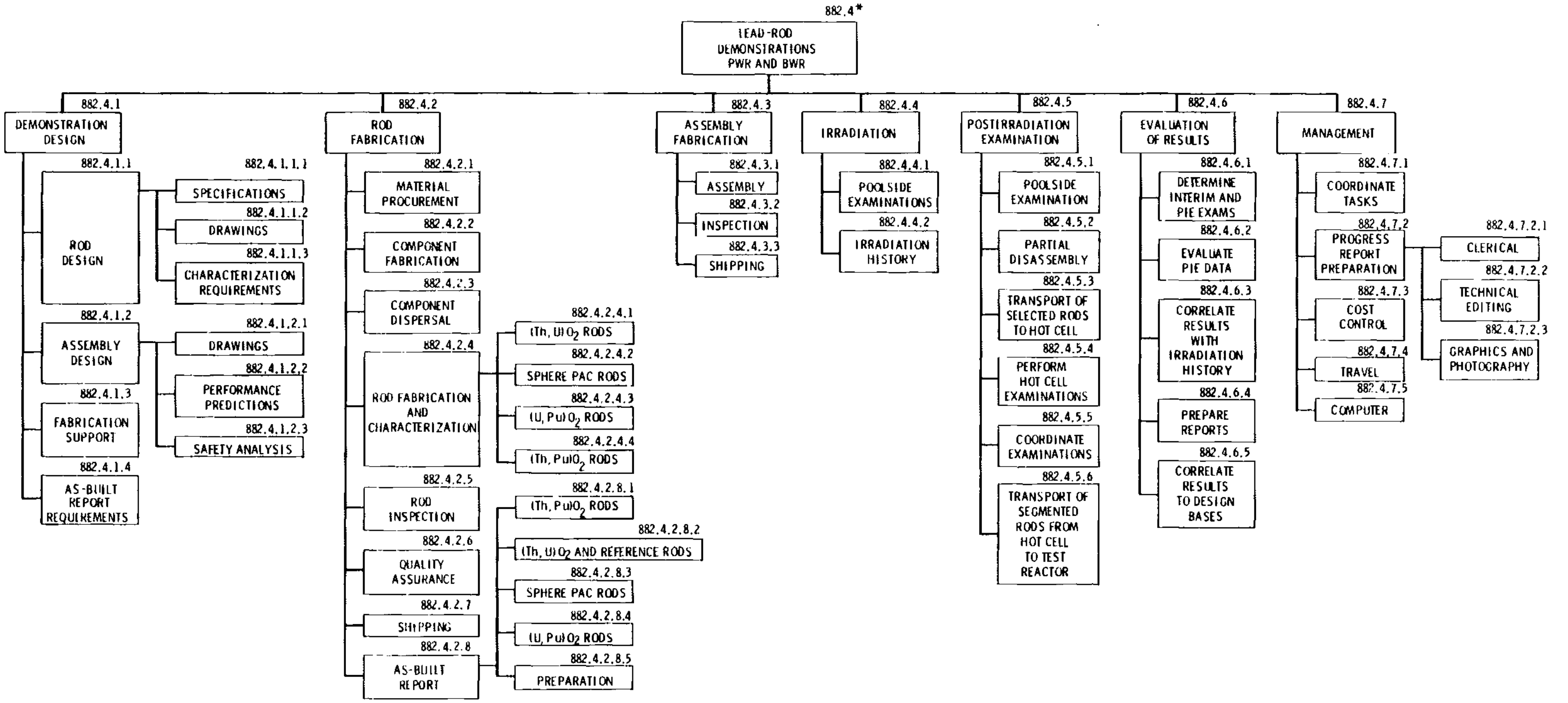
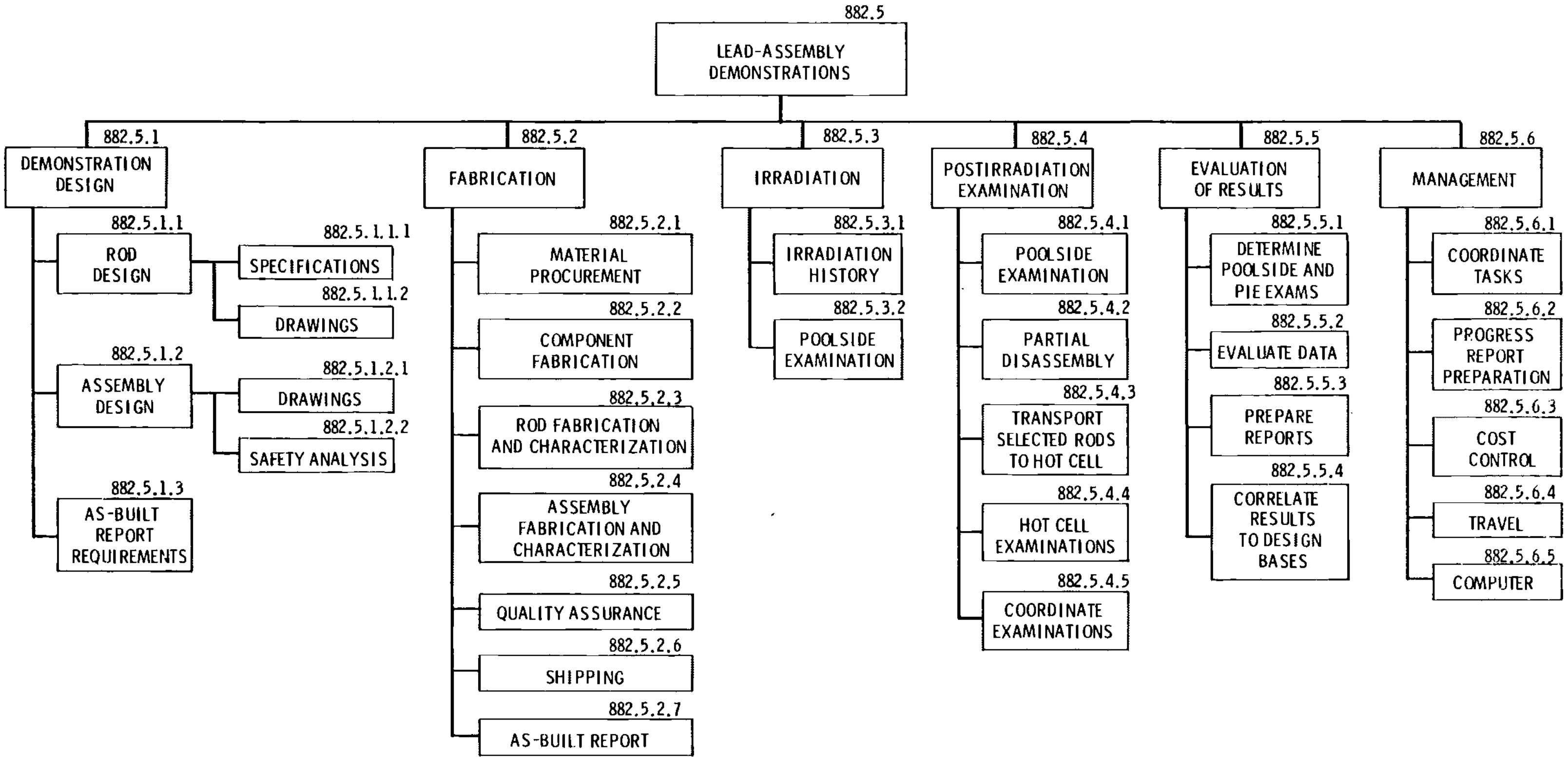


FIGURE 5. Work Breakdown Structure for FRAD Propensity for Failure Testing Activity



* WORK BREAKDOWN ITEM WILL HAVE SUFFICES "a" FOR PWR AND "b" FOR BWR ON SCHEDULES

FIGURE 6. Work Breakdown Structure for FRAD Lead-Rod Demonstration Irradiation Activity



*WORK BREAKDOWN ITEM WILL HAVE SUFFICES "a"
FOR PWR AND "b" FOR BWR ON SCHEDULES

FIGURE 7. Work Breakdown Structure for FRAD Lead-Assembly Demonstration Irradiation Activity

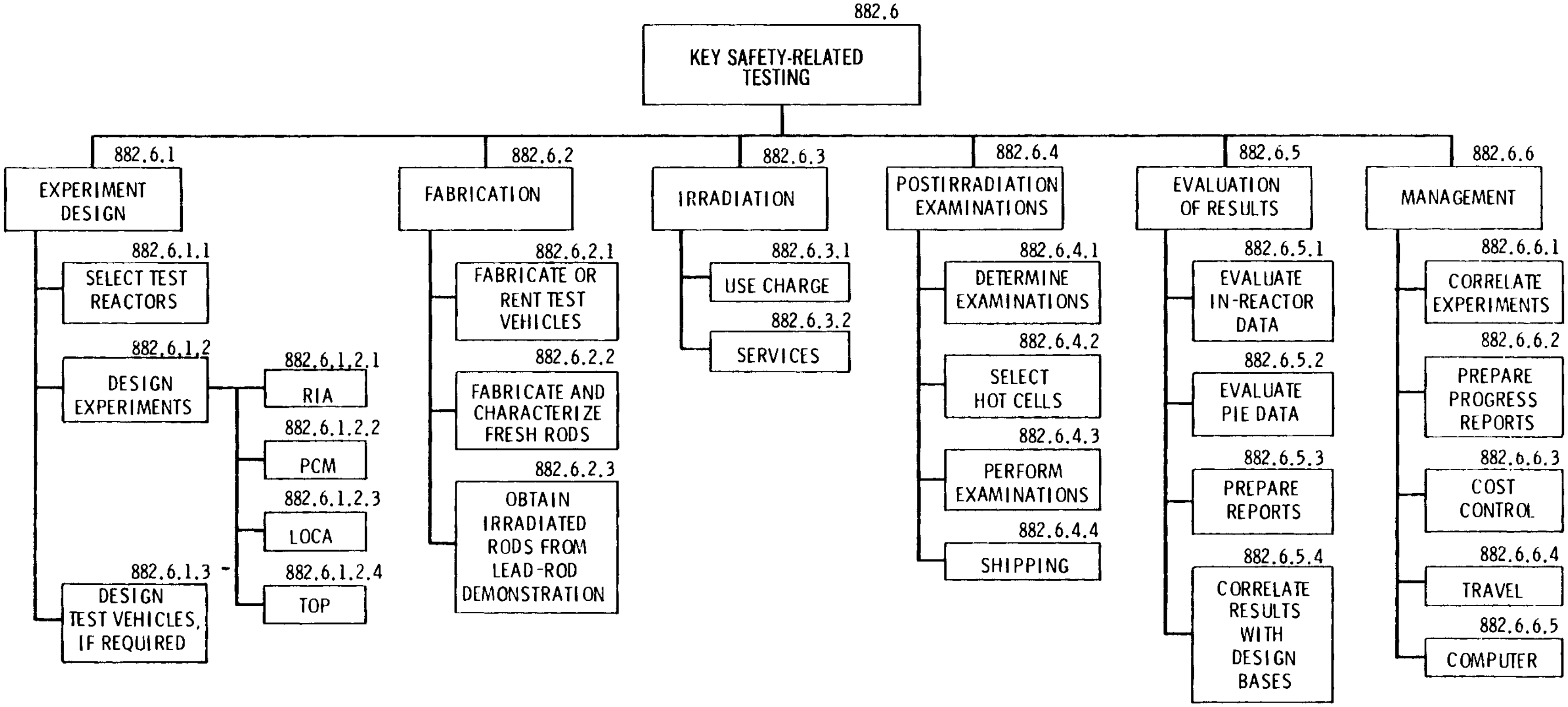


FIGURE 8. Work Breakdown Structure for FRAD Key Safety-Related Irradiation Testing Activity

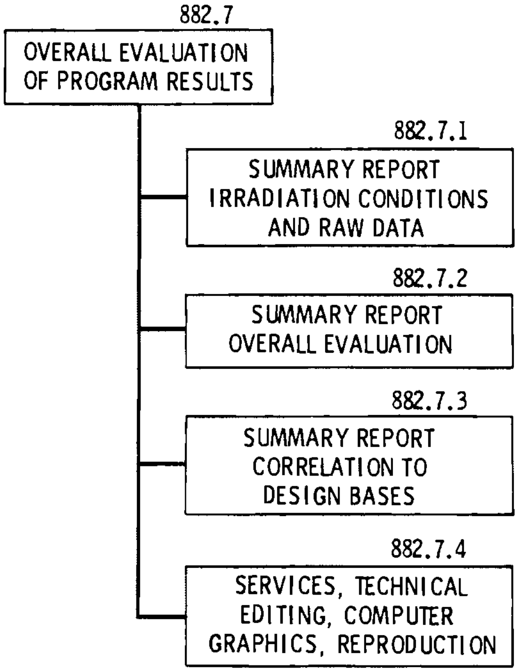


FIGURE 9. Work Breakdown Structure for FRAD Irradiations Evaluation Activity

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