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STEAM EXPLOSION PHENOMENA

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SANDIA STEAM EXPLOSION PROGRAM

OBJECTIVE: DETERMINE THE PROBABILITY OF A STEAM EXPLOSION CAUSING CONTAINMENT FAILURE

ADDRESS THE FOLLOWING TECHNICAL QUESTIONS:

1. FUEL-COOLANT MIXING
2. TRIGGERING
3. PROPAGATION
4. CONTAINMENT FAILURE PROBABILITY

STEAM EXPLOSION PHENOMENA - SANDIA

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STEAM EXPLOSIONS

PROGRAM STATUS

1. INTERIM CONCLUSIONS
2. CURRENT UNCERTAINTIES
3. CURRENT RESEARCH

FUEL-COOLANT MIXING

1. INTERIM CONCLUSIONS

INTERMEDIATE SCALE EXPERIMENTS INDICATE RAPID FUEL - COOLANT MIXING

- WATER WILL PROBABLY BE PRESENT IN THE LOWER PLENUM OR IN THE REACTOR CAVITY WHEN THE CORE IS MOLTEN (20-80%)
- EXPERIMENTS USING $Fe-Al_2O_3$ MELT SIMULANTS SHOW - MIXING OCCURS QUICKLY (< 0.1 SEC)
  - FUEL FRAGMENTS SMALL (~ 1-2 CM)

2. CURRENT UNCERTAINTIES

- MOLTEN MATERIAL MOTION PRIOR TO FUEL-COOLANT CONTACT
- MODE OF LOWER GRID PLATE FAILURE
- VESSEL GEOMETRY AT TIME OF FAILURE
- EFFECT OF SCALE ON MIXING
- BEHAVIOR OF CORIUM A, E, COMPARED TO SIMULANTS

FUEL-COOLANT MIXING

3. CURRENT RESEARCH

- BEGIN PHENOMENOLOGICAL MODELLING OF CORE MELTDOWN PROCESS
- ANALYZE POSSIBLE MODES OF GRID PLATE FAILURE
- CONTINUE FITS TESTS WITH SIMULANT AND PROTOTYPIC MATERIALS
- LARGE SCALE (~100 KG) EXO-FITS TESTS
- DEVELOP MIXING MODELS FROM EXPERIMENTAL DATA

EXPLOSION TRIGGERING

1. INTERIM CONCLUSIONS

- VIGOROUS EXPLOSIONS CAN BE TRIGGERED FOR REACTOR SIMULANT MATERIALS AT SMALL AND INTERMEDIATE SCALES.
- EXPLOSION BEHAVIOR DEPENDS ON INITIAL CONDITIONS: TRIGGER MAGNITUDE, AMBIENT PRESSURE, WATER TEMPERATURE, FUEL MELT COMPOSITION AND TEMPERATURE
- SPONTANEOUS EXPLOSIONS DO OCCUR IN SMALL AND INTERMEDIATE SCALE TESTS.
- SIMPLE MODELS CAN EXPLAIN EXPERIMENTAL RESULTS CONCERNING ARTIFICIAL TRIGGERING. THEY SUGGEST THAT EXPLOSION SUPPRESSION IS RELATED TO THE TRIGGER MAGNITUDE.

EXPLOSION PROPAGATION

1. INTERIM CONCLUSIONS

- THE EXPLOSION CONVERSION RATIO IS DEPENDENT UPON SCALE
- SMALL SCALE TESTS: 0-20%
  INTERMEDIATE SCALE TESTS: 0-2%
- INTERMEDIATE SCALE TESTS (FUEL MASS $\simeq$ 5 KG)
  SHOW PROPAGATION OF THE EXPLOSION THROUGHOUT
  THE MIXTURE (V = 300 - 500 M/S)
  WITH HIGH PEAK PRESSURES (P > 15 MPA)
- TRANSIENT MODELS ARE BEING APPLIED TO THE EXPLOSIVE PROPAGATION AND EXPANSION

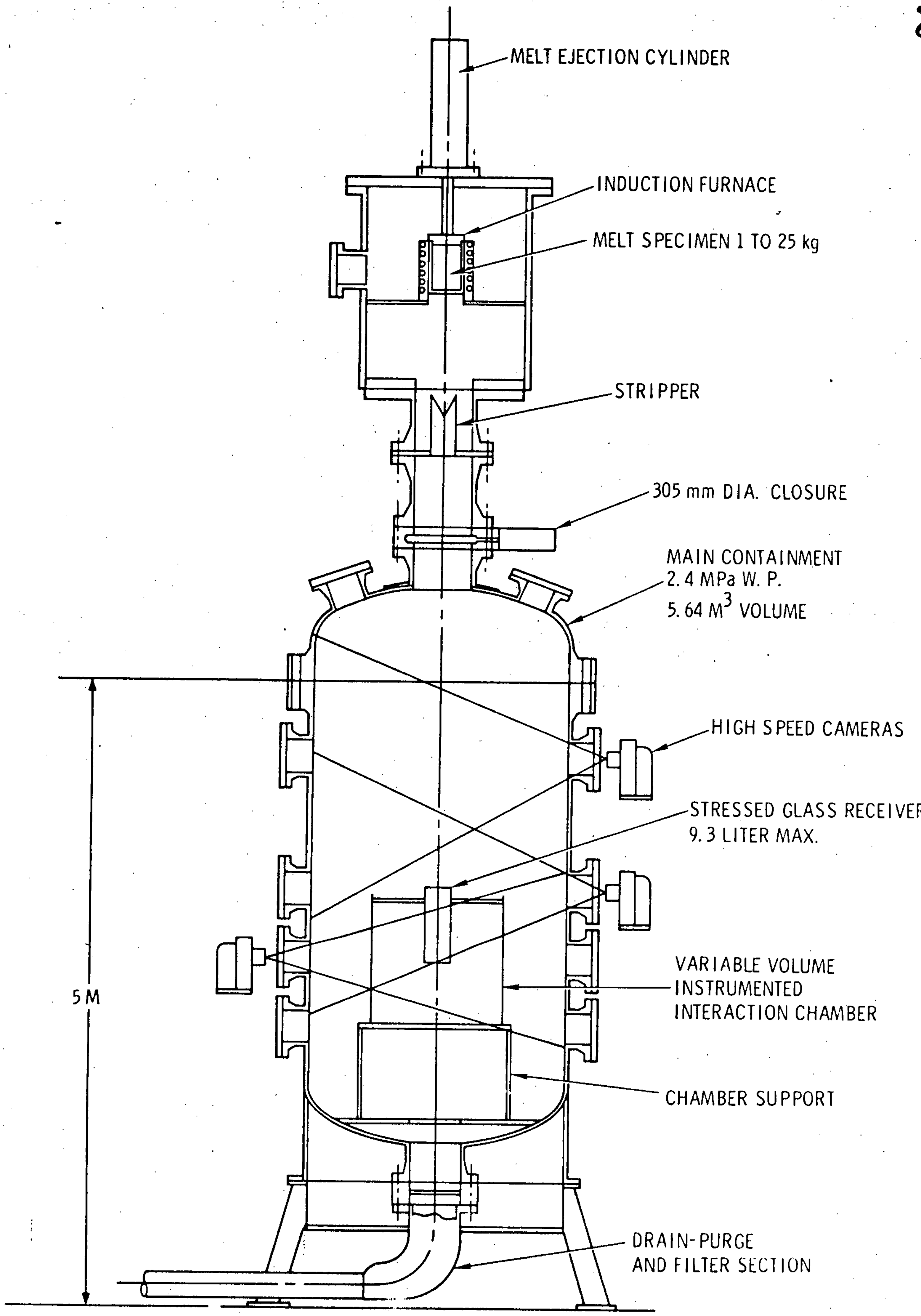

FIGURE 1. "FITS" FACILITY DESIGN

EXPLOSION TRIGGERING AND PROPAGATION

2. CURRENT UNCERTAINTIES

- OCCURRENCE OF STEAM EXPLOSION AS FUNCTION OF INITIAL CONDITIONS
- DEPENDENCE OF CONVERSION RATIO ON INITIAL CONDITIONS

INITIAL CONDITIONS INCLUDE:

- MELT COMPOSITION
- FUEL AND COOLANT MASSES
- FUEL AND COOLANT TEMPERATURES
- AMBIENT PRESSURE
- TRIGGER MAGNITUDE

EXPLOSION TRIGGERING AND PROPAGATION

3. CURRENT RESEARCH PLANS

- SMALL SCALE EXPERIMENTS (0.1-15 G)
  - FE, FEO_X, ZRO_X, CORIUM A, E
  - MAGNETIC PRESSURE TRIGGER AND BRIDGEWIRE
  - P_∞, T (MELT), T (COOLANT)

- INTERMEDIATE SCALE EXPERIMENTS

  A. FITS (1-20 KG)
  - $FE\text{-}Al_2O_3$, FEO_X, CORIUMS EVENTUALLY
  - MELT, COOLANT MASSES AND TEMPERATURES
  - $P_\infty = 1 \rightarrow 10$ BARS
  - MEASUREMENTS = P, T, F, PHOTOGRAPHY
  - DERIVE: CONVERSION RATIOS, MIXING AND PROPAGATION DYNAMICS, EXPANSION PHASE AND DAMAGE MECHANISMS; INCOHERENT (MULTIPLE) EVENTS WITH CUMULATIVE DAMAGE.

  B. EXO-FITS (~100 KG)
  - THERMITES - $FE\text{-}Al_2O_3$, CORIUM A-R

EXPLOSION TRIGGERING AND PROPAGATION

3. CURRENT RESEARCH (CONT.)

- ANALYSIS AND MODELLING
  - DEVELOP DYNAMIC FILM BOILING MODEL FOR TRIGGERING AND FILM COLLAPSE FOR DIFFERENT INITIAL CONDITIONS
  - PROPAGATION MODEL TO ANALYZE NELSON'S SINGLE DROP EXPERIMENT (CSNI CANDIDATE EXPERIMENT)
  - TRANSIENT MACROSCOPIC 1-D PROPAGATION MODEL TO ANALYZE FITS EXPERIMENTS
  - EXPANSION MODEL TO PREDICT THE THERMAL TO MECHANICAL CONVERSION RATIO IN FITS AND OTHER EXPERIMENTS

CONTAINMENT FAILURE PROBABILITY

THERE ARE TWO POSSIBLE MODES OF CONTAINMENT FAILURE DUE TO IN-VESSEL OR EX-VESSEL STEAM EXPLOSIONS

- MISSILE GENERATION BY THE EXPANSION OF THE FUEL-COOLANT MIXTURE AND ACCELERATION OF A SLUG (SOLID, LIQUID FUEL OR WATER) AND SUBSEQUENT IMPACT ON THE VESSEL STRUCTURE
- LEAKAGE THROUGH CONTAINMENT PENETRATIONS CAUSED BY GROSS MOTION OF THE REACTOR VESSEL, COMPONENTS OR SURROUNDING STRUCTURE.

FOLLOWING INTERIM CONCLUSIONS ARE ONLY APPLICABLE TO ZION, INDIAN POINT AND SIMILAR CONTAINMENTS.

CONTAINMENT FAILURE PROBABILITY

I. INTERIM CONCLUSIONS

IT IS UNLIKELY THAT LARGE MASS MISSILES WILL BE GENERATED

- THE IN-VESSEL EXPLOSION CAN ACCELERATE A SLUG TO IMPACT WITH THE VESSEL HEAD AND POSSIBLY GENERATE A MISSILE
- FIVE DIFFERENT LOADING CONDITIONS ON THE VESSEL HEAD WERE EXAMINED
- IN ALL THE CONDITIONS, VESSEL HEAD FAILURE FIRST OCCURRED AT THE TOP OF THE HEAD
- THIS LOADING PATTERN SUGGESTS A LOCAL FAILURE WOULD OCCUR RATHER THAN A CIRCUMFERENTIAL RIP

SUMMARY OF VESSEL FAILURE EVALUATION

CASE	FAILURE AT TOP OF HEAD[1]	FAILURE AT STUDS[1]	FAILURE AT VESSEL BELOW FLANGES[1]
300 MJ HEMISPHERICAL SLUG	YES[2]	POSSIBLE	NO
3000 MJ HEMISPHERICAL SLUG	YES	POSSIBLE	POSSIBLE
300 MJ SPHERICAL SLUG	POSSIBLE	POSSIBLE	NO
LASL P(T) HISTORY	NO	NO	NO
UPPER CORE SUPPORT PLATE	---	NO	NO

[1]. "YES" OR "NO" INDICATES BOTH CRITERIA AGREE
"POSSIBLE" INDICATES ONLY ONE CRITERION PREDICTS FAILURE

[2]. STRAIN FAILURE ASSUMED BECAUSE OF SMALL MARGIN

SMALL MASS MISSILES COULD BE GENERATED BY AN EXPLOSION

- THE SLUG IMPACT WITH THE HEAD CAN EJECT A SMALL MISSILE (E.G. CONTROL ROD DRIVE)
- THE EJECTED MISSILE VELOCITY CAN BE IN THE RANGE OF 40-400 M/S
- THE MISSILE FIRST MUST PENETRATE THE CONTROL ROD MISSILE SHIELD TO POSE A THREAT TO THE CONTAINMENT
- LOW VELOCITY MISSILES CANNOT PENETRATE THE SHIELD
- AS THE VELOCITY INCREASES, THE DEPTH OF PENETRATION INCREASES: HOWEVER, THE MISSILE IS DESTROYED DURING PENETRATION
- NO SPALLATION OF THE CONCRETE SHIELD IS PREDICTED (BY 30 MS)

CONTAINMENT FAILURE PROBABILITY

2. CURRENT UNCERTAINTIES

- RELIABILITY OF CURRENT ANALYSIS CONCERNING MISSILE GENERATION AND DAMAGE POTENTIAL
- EFFECT ON DIFFERENT CONTAINMENT SYSTEMS
  - BWR - MARK I
  - BWR - MARK II
  - PWR - ICE CONDENSER
- HOW DOES SYSTEM GROSS MOTION, CAUSED BY STEAM EXPLOSIONS, COMPARE TO SEISMIC AND DBA CAUSES
- MITIGATION EFFECTS AND MARGIN OF SAFETY DUE TO
  - UPPER INTERNAL STRUCTURE
  - LOWER PLENUM FAILURE
  - OBSTRUCTING OBJECTS (MISSILE SHIELD)
- DISAGREEMENT BETWEEN CSQ CALCULATIONS AND SOME EMPIRICAL CORRELATIONS (WHICH PREDICT 1-10 M PENETRATIONS FOR SMALL MISSILES)

CONTAINMENT FAILURE PROBABILITY

3. CURRENT RESEARCH

- EVALUATE POSSIBILITY OF LEAKING AT CONTAINMENT PIPING PENETRATIONS DUE TO
  - IN-VESSEL STEAM EXPLOSION
  - VESSEL MELT-THROUGH OR LOWER PLENUM FAILURE BY STEAM EXPLOSION
  - EX-VESSEL STEAM EXPLOSION
- REFINE MISSILE GENERATION ANALYSIS
  - MITIGATION DUE TO LOWER PLENUM FAILURE
  - MITIGATION EFFECTS OF UPPER INTERNAL STRUCTURE
  - MORE CONSERVATIVE ASSUMPTIONS WHERE INDICATED BY EXPERIMENT OR THEORY
- SCALED FLUID-STRUCTURE EXPERIMENTS

STEAM EXPLOSIONS
STATE-OF-TECHNOLOGY

1. CONVERSION RATIOS FOR LARGE SCALE EXPLOSIONS ARE PROBABLY OF ORDER 2%, CONSERVATIVELY BOUNDED BY 15%.
2. FRACTION OF MOLTEN CORE WHICH CAN PARTICIPATE IN EXPLOSION IS PROBABLY OF ORDER 20-50%, CONSERVATIVELY BOUNDED BY 100%.
3. ESTIMATES OF THE PROBABILITY OF LARGE MASS MISSILE GENERATION ARE COMPLETELY THEORETICAL. ALTHOUGH DEEMED UNLIKELY, ADDITIONAL ANALYSIS AND EXPERIMENTATION WOULD BE PRUDENT.
4. ALTHOUGH SMALL MASS MISSILES COULD BE GENERATED THEIR DAMAGE POTENTIAL SEEMS TO BE SMALL. PRUDENCE, AGAIN, WOULD REQUIRE ADDITIONAL RESEARCH.
5. CONTAINMENT FAILURE DUE TO STEAM EXPLOSION SHOCK WAVES IS UNLIKELY.
6. STEAM OVER-PRESSURIZATION IS MORE LIKELY TO RESULT FROM EFFICIENT BOILING RATHER THAN FROM INEFFICIENT STEAM EXPLOSIONS.