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SAFETY CONCERNS AND SUGGESTED DESIGN APPROACHES TO
THE HTGR REFORMER PROCESS CONCEPT

MASTER

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TO THE HTGR REFORMER PROCESS CONCEPT

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ABSTRACT

This report is a safety review of the High Temperature Gas-Cooled Reactor Reformer Application Study prepared by Gas-Cooled Reactor Associates (GCRA) of La Jolla, California. The objective of this review was to identify safety concerns and suggest design approaches to minimize risk in the High Temperature Gas-Cooled Reactor Reformer (HTGR-R) process concept.

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SAFETY CONCERNS AND SUGGESTED DESIGN APPROACHES
TO THE HTGR REFORMER PROCESS CONCEPT

INTRODUCTION

The EG&G-Idaho Safety Division was asked to review the High Temperature Gas-Cooled Reactor Reformer (HTGR-R) Application Study [prepared by Gas-Cooled Reactor Associates (GCRA), of La Jolla, California]¹ and to identify potential hazards and their possible solutions.

The application study provides information on high temperature gas-cooled reactor process heat utilization via a thermal-catalytic reformer produced process gas. In this process, a portion of the reactor thermal energy is converted to a storable, transportable energy form through the use of the highly endothermic, reversible chemical reaction $\text{CH}_4 + \text{H}_2\text{O} + \Delta H \rightarrow \text{CO} + 3\text{H}_2$. The reformer is direct cycle if heated by the reactor primary coolant, and indirect cycle if heated by an intermediate heat transport medium. The hydrogen and carbon monoxide produced in the reformer are delivered to the industrial user via a thermochemical pipeline (TCP), which may be either closed cycle or open loop. The reformer gas enters a methanator, at the users plant, where it is transformed back to methane and water, thereby yielding thermal energy.

The HTGR-R is the only nuclear concept having the potential for filling many U.S. industrial process heat needs and reducing national dependence upon foreign oil and gas in this industrial sector.

The objectives of this safety review, as determined by the Nuclear Energy Programs Organization within EG&G Idaho, are described in the following task list:

1. Review the HTGR Program Hazards Evaluation.

2. Identify safety concerns and evaluate risk associated with both the indirect cycle and the direct cycle reformer concepts with emphasis upon those concerns associated with using toxic and combustible materials within, or in proximity to, an HTGR.
3. Review and document relevant safety and licensing approaches used in nuclear process heat applications and in the synfuels industry.
4. Recommend design approaches, operating procedures, and licensing bases for the HTGR-R plant to minimize safety problems and licensing difficulties.

REVIEW OF THE HTGR REFORMER APPLICATION STUDY HAZARDS EVALUATION

The review of the HTGR-R applications study and the related HTGR Accident Initiation and Progression Analysis,² by members of the EG&G-Idaho Safety Division, addressed the following questions:

1. Does the application document fulfill its stated purpose of:
(a) evaluating the suitability of the HTGR-R as a potential near-term Lead Project, and (b) determining the merits and appropriateness of an HTGR Program strategy based upon such a Lead Project?
2. Does the document convey enough safety-related information so that preconceptual safety issues can be adequately evaluated?
3. What is the credibility basis for judging the technical adequacy of structures, materials, and processes: (a) theoretical; (b) engineering calculation; (c) experimental; (d) prototype applications; (e) commercial applications; and/or (f) statistical?

The general consensus of the review group is that the document does present a number of firm arguments and options for an HTGR-R Lead Project indicating that the program would possess significant merit. However, the application study, as written, does not permit a safety feasibility determination because of the limited safety information. It is foreseen that safety and material issues may be the primary barriers to development within the near term. We believe that a systems safety approach would greatly enhance the credibility and stature of the document. If this recommendation was implemented, the needs of the readership would be met more likely. At this time, there appears to be three categories of readership: (a) the HTGR Program participants who must agree upon a design and focus upon a development effort; (b) the licensing and safety personnel who must review and render opinions based upon what they read; and (c) the funding organizations who must be convinced that the program warrants the

financial and technical support and effort. The study, as written, strongly favors the needs of the first reader while meagerly fulfilling the needs of the second. Whether the needs of the third reader are fulfilled is questionable due to the limited safety analysis.

A review of the reference documents raises many safety-related issues that are not adequately resolved by the existing hazards evaluation. Generically, the issues relating to safety that need to be addressed more fully in the hazards evaluation are:

1. Questions concerning structural material properties under the stated process conditions, e.g., pressure, temperature, material interface, and nuclear environment
2. The initiating causes and consequences of combustible materials contacting nuclear materials
3. The initiating causes and consequences of combustible materials admixing with air or other oxidizers
4. The design barriers limiting the admixture of materials described in Items 2 and 3 above
5. Nuclear reactor anomalies and their interaction effects upon reformer function
6. Anomalous behavior of the reformer and its interaction effects upon reactor function
7. Potential toxic and explosion interaction effects upon personnel

A critical problem facing a safety-oriented reviewer is that of establishing a basis for judging technical credibility as it relates to the

assessment of safety problems. It appears that the credibility of the application study is based primarily upon theoretical and engineering design calculation. We believe that if experimental, experience, and statistical bases exists, they should be strongly emphasized in the study.

DESCRIPTION OF SAFETY AND RISK MANAGEMENT TECHNIQUES AND THEIR APPLICABILITY TO DEVELOPMENT OF THE HTGR-R PROGRAM

It is probable that safety issues, and their relationship to the licensing process, could severely inhibit the development of the HTGR-R Program. To prevent this, we recommend a systems safety approach to identify the inherent risks, suggest methods of risk reduction, and produce an acceptable program.

The system safety methodology used by the Department of Energy, the Nuclear Regulatory Commission, and EG&G Idaho, and recommended for consideration in the HTGR Reformer Project, is known as the Management Oversight Risk Tree (MORT) Methodology. MORT is a comprehensive analytical procedure that provides a disciplined method for determining the causes and contributing factors of major accidents. Alternatively, it serves as a tool to evaluate the quality of an existing safety system. While similar in many respects to Fault Tree Analysis, MORT is more generalized and presents over 1500 specific elements of an ideal "universal" management program for optimizing safety.

MORT possesses four key innovative features which are congruous with a goal-oriented, high performance, complex management system. They are:

1. An analytical "logic tree" or diagram from which MORT derives its name "Management Oversight and Risk Tree." This diagram arranges safety program elements in an orderly, coherent, and logical manner.
2. Schematic representation of a dynamic idealized or "universal" safety-system model by using Fault Tree Analysis methodology.
3. Methodology for analyzing a specific safety program through a process of evaluating the adequacy of implementing the individual safety-system elements.

4. A collection of philosophical statements and general advice relative to the application of the MORT system safety concepts and a list of criteria to be used to assess effectiveness.

As a safety-management program, MORT has been designed to:

1. Prevent safety-related oversight, errors, and omissions
2. Result in identification, assessment, and referral of residual risks to proper management levels for appropriate action
3. Optimize allocation of resources available to the safety program and to individual hazards control efforts.

Examples of MORT logic application to the HTGR reformer concept are presented in Figures 1-4. Highlighted on the trees in Figure 4 are those areas which the applications study addresses to some degree. A review of the limited risk information provided, relative to MORT requirements, indicates the magnitude of the effort required to entice industrial funding support.

Figure 1. MORT--The Management Oversight and Risk Tree.


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graph TD
    SSC[SYSTEM SAFETY DEVELOPMENT CENTER] --- J(( ))
    J --- EG[EG&G]
    J --- DOE[DOE]
  
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Figure 2. Risk Management Tree.

Figure 3. Safety Analysis Requirements Tree.

Figure 3. Safety Analysis Requirements Tree (cont.)

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Figure 4. Safety Analysis Process Tree.

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Figure 4. Safety Analysis Process Tree (cont.)

Figure 4. Safety Analysis Process Tree (cont.)

IDENTIFIED SAFETY CONCERNS AND SUGGESTED APPROACHES

Experience has shown that accidents rarely are simple and almost never result from a single cause. Rather, they are multifactorial and develop from clearly defined sequences of events which may involve performance or design errors, changes, oversights, or omissions. The identified safety concerns addressed in this section are technical assumptions of those principle conditions or events, unique to the HTGR-R, which could contribute to or trigger an accident within the HTGR-R system. It should be noted that these are perceptual concerns only and resulted from reviewing only the referenced information. They are not meant to be definitive statements of risk associated with the HTGR-R concept.

Categorizing the list of safety concerns is advantageous due to the number of them, their complexity, and the requirements needed for their resolution. Figure 5 describes what appears to be the most generic and consistent classification based upon the following logic:

1. The safety concerns of the system: structural and process material concerns.
2. The safety concerns of potential energy-release modes and mechanisms: structural, process, and human failures.
3. The safety concerns associated with consequences of energy release:
 - a. Organic/combustible--nuclear material interface
 - b. Organic/combustible--air admixture
 - c. Organic/combustible--toxic material interface with personnel.

Figure 5. Categories of identified safety concerns.

Identified Safety Concerns Associated with HTGR-R Structural and Material Properties

The HTGR-R concept, by its very nature, is pushing present technology to a limit. As such, it is essential that questions be asked concerning structural and material properties of the system.

Process Conditions

Listed below are some issues and resolutions regarding process conditions.

1. Issue: Are all structural materials qualified for their normal temperature and pressure conditions?

Resolution: Ensure qualification through materials research, ASME Code qualification and pedigree and document conformance in a safety report.

2. Issue: Are all structural materials qualified for abnormal temperature and pressure conditions? What are the expected limits of pressure and temperature? What are the consequences of higher-than-expected pressure and temperature transients upon all structural materials?

Resolution: Ensure qualification, as stated in Item 1 above, or demonstrate that the consequence is manageable and within the risk envelope.

3. Issue: Are structural materials qualified for the process material interface that will exist under normal and abnormal conditions?

Resolution: Ensure qualification through a materials research program and document conformance in a safety report.

4. Issue: Are the reaction kinetics well known for the reformer and methanator systems? Can temperature and pressure transients destructively alter the kinetics? Can the catalytic rates be altered?

Resolution: Determine the temperature, pressure, and catalytic boundary conditions and document them in the safety report.

5. Issue: What are the potential problems with the nickel catalysts of the reformer and methanator systems during the: (a) insertion phase; (b) oxide-reduction phase; (c) reforming and methanation phase; (d) abnormal or emergency phase; and (e) extraction phase? Can the catalysts be poisoned? If so, by what? Are there impurities in the material feedstock or structural materials? Are there other inadvertent and nonrecognized catalysts in the system? Are there any nuclear radiation--nickel catalyst interface problems? What are the details of the pyrophoric hazard--personnel interface and the toxic (nickel carbonyl)--personnel interface?

Resolution: Characterize and document the problems. Perform a cause-consequence analysis.

6. Issue: Is the Wigner effect a consideration for safe operation of the HTGR? Is annealing required?

Resolution: Evaluate and document it in the safety report.

7. Issue: Is the hydrogen formed within the reformer initially in the nascent (monoatomic) form? Can this form affect the structural materials differently than the diatomic form?

Resolution: Do an evaluation. The reactivities and energy yield of monoatomic hydrogen are considerably different than the diatomic form. This is very apparent under flammability conditions.

8. Issue: Are the flammability characteristics of hydrogen modified by the irradiation environment?

Resolution: Do an evaluation. There is some evidence that the flammability characteristics of hydrogen may be modified by exposure to ionizing radiation. There are also the questions of whether the threshold of ignition and the flame velocity can be increased or decreased by irradiation.

9. Issue: Are the reformer fluids in the direct cycle activated by the neutron environment.

Resolution: Evaluate and document this in the safety report.

Impurities

The following lists some issues and resolutions regarding impurities at the structural process interface.

1. Issue: What are the expected types and quantities of impurities in: (a) the chemical feedstock; and (b) in structural materials? Are they variable with time, vendor or supplier, or system degradation?

Resolution: Characterize type and quantity of impurity expected. Sample and assess all structural and process materials.

2. Issue: What are the effects of impurities upon the reactor system? Can the helium purification system cope with potentially severe impurity injection? Would severe impurities act as trigger events (precursor) only, or as a major abnormal event?

Resolution: Evaluate and perform a cause-consequence analysis.

3. Issue: Could small particles (physical impurities) in the process material flows produce erosion within the process system that could lead to a loss of structural integrity? Possible targets may be tube sheets, pipes, elbows, valves, or other flow interruptors, constrictors, or directionalizers.

Resolution: Evaluate and perform a cause-consequence analysis.

4. Issue: What are the effects of chemical impurities within the process system? Nitrogen gas contamination in the system may lead to the formation of ammonia which can produce nitriding of structural steels at high temperatures in the presence of water. If ammonium hydroxide were formed, stress corrosion would occur in ferrite steels. If sulphur were present (either as an oxide or sulfide contaminant in the methane feedstock or as a component of coal in the gasification process), nickel-bearing alloys may be attacked through a process called sulphidation. Cobalt alloys have a longer life than nickel alloys do in a sulphur environment.

Resolution: Evaluate and perform a cause-consequence analysis.

Corrosion

Listed below are issues and resolution regarding corrosion problems within the process system.

1. Issue: What are the types of corrosion problems expected within the system?

Resolution: Evaluate and document this in the safety report.

2. Issue: How is corrosion controlled within the system?

Resolution: Document this in the safety report.

3. Issue: What are the effects of corrosion within the system?

Resolution: Evaluate and demonstrate that corrosion will not lead to a destructive loss of structural integrity.

4. Issue: What is the likelihood of water corrosion of carbon steel in the thermochemical pipeline (TCP) due to the formation of carbonic acid (H_2CO_3) resulting from water and carbon dioxide reactions?

Resolution: Evaluate this. Carbon steel pipe lined with a thin layer of austenitic stainless steel is very resistant to corrosion. Control of the size, shape, and distribution of nonmetallic impurities in pipeline steel is critical to its strength and corrosion resistance. A technique for evaluating the real-time corrosion status of a system is called "Sentry Drilled Pipe." A small hole is drilled partly through the wall of a pipe at those areas where corrosion is expected, e.g., elbows, and as corrosion occurs, the first penetration will be at the sentry hole. This will result in a small leak, flare, or alarm that is immediately detectable and not serious. By knowing the wall thickness at the sentry hole, a level of corrosion is known.

5. Issue: What is the likelihood of water corrosion of stainless steel occurring if halides (F, Cl, Br, I) are present within the process material?

Resolution: Evaluate the likelihood of these chemical species being present in the system and control concentration.

6. Issue: Will wet-dry conditions exist in any part of the system, e.g., TCP, that could lead to stress corrosion cracking? Wet-dry conditions in large turbogenerators, on the low pressure side, have resulted in stress corrosion cracking in high-strength steels.

Resolution: Evaluate and document this in the safety report.

7. Issue: Will a high pressure CO and CO₂ atmosphere within the carbon steel TCP produce stress corrosion cracking?

Resolution: Evaluate this. (Consider using austenitic steel liners.)

Embrittlement

The following issues and resolutions regard embrittlement within the systems.

1. Issue: What is the likelihood of hydrogen embrittlement occurring in the reformer, TCP, and methanator systems? Is austenitic stainless steel used?

Resolution: State the potential problems and evaluate them. Austenitic stainless steels or liners are recommended.

2. Issue: Are there any ferritic steels in the system that interface with hydrogen? What would be the effects of embrittlement and the attendant decrease in toughness?

Resolution: Evaluate these potential problems. Austenitic steel alloys may be used to control the hydrogen embrittlement problem, although there are limitations of time, temperature, pressure, and cost. Ferritic steels are very susceptible to embrittlement.

3. Issue: Are there other embrittlers within the HTGR-R system besides hydrogen?

Resolution: Do an evaluation; for example, under given conditions, the lead oxide found in coal can be a severe metal embrittler. This may be a consideration in the coal gasification interface.

4. Issue: Will high-pressure hydrogen (1000 psia) produce an enhanced crack growth rate per loading cycle in carbon steel?

Resolution: A cursory review of an article by R. J. Walter and W. T. Chandler^a indicates that hydrogen does enhance the crack growth rate per loading cycle.

Identified Safety Concerns Associated with
HTGR-R Structural, Process, and Human Failures

Three classes of failures appear to be common to the infinite number of HTGR-R accident scenarios that could be postulated. They are structural, process, and human failures. Structural failures are defined as faults that result in loss of integrity or function of some structural component. Process failures result from faults in energy flow or process materials. Human failures are defined as faults in action, analysis, decisions, observations, calculation, etc. All accidents possess these three classes of failures somewhere within the accident-events sequence. These failures may act as causative factors (preparatory and trigger), contributing conditions, or consequence-effects, and they may change character with time.

a. R. J. Walter and W. T. Chandler, "Crack Growth in ASME SA-105 Grade II Steel in Hydrogen at Ambient Temperature," Effect of Hydrogen on Behavior of Materials, New York, AIME, 1976, p. 273.

Structural Failures

Figure 6 is a simplistic matrix tree relating the HTGR structural components to the forms of energy within the system, and the possible sources of structural failure. By producing various combinations and permutations of the structure-energy-failure sets, one can identify a number of scenarios that need to be addressed from a safety point of view.

Process Failures

The following process failures are identified safety concerns within the HTGR-R system. All resolution comments would express the need to evaluate.

1. Issue: The thermal explosion potential in the reformer and methanator due to a failure in heat transfer or a change in reaction rates?
2. Issue: Anomalous behavior of the reformer and its effect upon reactor operation?
3. Issue: Anomalous behavior of the reactor and its effect upon reformer operation, e.g., HTGR-R representative plant transients?
4. Issue: Anomalous behavior within the TCP?
5. Issue: Anomalous behavior within the methanator?

Human Failures

The following human failures are identified safety concerns within the HTGR-R system. All resolution comments would express the need to evaluate.

1. Issue: A failure in determining the causes and contributing factors for potential HTGR-R accidents.

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Figure 6. Structural component, energy, failure source matrix for the HTGR-R system.

2. Issue: A failure to evaluate the quality of an existing safety system.
3. Issue: A failure to prevent safety-related oversights, errors, and omissions.
4. Issue: A failure to identify, assess, and refer residual risks to proper management levels for appropriate action.
5. Issue: A failure to allocate available resources to a safety program and the hazard-control effort.

Identified Safety Concerns Associated with
Organic/Combustible Material Interface with Nuclear
Process and Structural Materials

If the HTGR concept did not have any severe technical, operational, and licensing problems, and if industry safely processed large quantities of organic/combustible materials every day, then it would appear that the major safety concerns of the HTGR-R concept are predicated upon the nuclear-organic/combustible materials relationship. If the factors constituting this relationship were well defined as to type and magnitude, then it would appear that through adjustment of the magnitudes of the various factors, an HTGR-R solution could be found that is acceptably safe. For example, it can easily be demonstrated that there are now numerous operations that result in organic/combustible materials being used within or near a nuclear reactor; e.g., utility fuels and lubricants used within the system, railway and truck transportation of organics (fuels, etc.) to or near a reactor complex, or industrial plants near a reactor complex operating under normal or emergency conditions. It is apparent that the magnitude of nuclear-organic/combustible material interface is the parameter to be controlled. Figure 7 describes both the factors defining the nuclear-organic/combustible material relationship and the controllers

Figure 7. Factors establishing the nuclear-organic/combustible material interface.

(limitations, constraints, barriers, structures, protectors) of that interface. It is apparent that some material factors may become controllers.

Considering the many variables of the safety equation, it appears there would be little safety concern (about this kind of accident potential) if there were assurances that no structural failures could occur that would result in a nuclear-organic/combustible material interface (e.g., admixing, contacting, absorbing). To effect this goal, a fault tree-materials pathways analysis is recommended that would evaluate the number of ways the material interface could be produced. Adequate controller-protectors could then be designed into the system. Perhaps a "diversion path analysis" code could be modified to perform the materials pathway analysis since they appear to be based upon similar assumptions.

The ultimate issues that must be addressed in a safety analysis of the HTGR-R system are:

1. Will normal or abnormal function of the nuclear process heat source adversely affect the structure or function of the process plant and delivery system?
2. Will normal or abnormal function of the process plant and delivery systems adversely affect the nuclear process heat source?
3. What are the risks (probability of occurrence x consequence) of the interaction?
4. Are the risks acceptable?

These issues are not adequately addressed in the safety section of the HTGR reformer application study because, obviously, this document was not meant to be a safety analysis report.

Identified Safety Concerns Associated with
Organic/Combustible Material Admixture with Air

A review of the applications study resulted in the following identified safety concerns:

1. Issue: The number and kinds of failure events in the HTGR-R system that could result in an admixture of organic/combustible material and air.

Resolution: An organic/combustible admixture with air is possible through both human error and structural failure occurring in either the direct or indirect cycle reformers, the thermochemical pipeline, the gas-storage system, or the methanator trains. It appears there are a large number of possible failure scenarios due to the complexity of the system, e.g., pressure, temperature, process characteristics, radiation environment, system dynamics, interrelationships between the nuclear heat source and reformer systems, characteristics of cavity liners, penetrations, closures, pumps, valves, thermal barriers, and control systems. We recommend a failure initiation and progression analysis be conducted to evaluate all credible failure events.

2. Issue: Predicting the combustible gas source term for a given failure event.

Resolution: The combustible gas source term is a description of the type and quantity of combustible material that can enter into a reaction. For any given scenario, there appears to be difficulty in predicting the chemical composition and the mass release per unit time. We recommend an experimental program be initiated to determine bounding data.

3. Issue: The amount of organic/combustible material released in a postulated failure event.

Resolution: For any given scenario, there appears to be comparatively large mass quantities of material released. Because the mass of the fuel relates, in a very complex manner, to the energy yield of an exothermic event, all efforts should be made to limit the release. This could be effected through limiting the size of the containment volumes, the use of special closures, preprogrammed failure routes, double and triple containments, etc.

4. Issue: The number and types of ignition mechanisms present within the system.

Resolution: The following ignition mechanisms may be potential modes of initiation of fire and/or explosion:

- a. Inverse Joule-Thompson effect resulting from a pressurized gas leak from a system (pressurized H_2 gas heats upon expansion)
- b. Electrostatic ignition upon gas release, e.g., charge separation, St. Elmo's fire, ground currents, lightning
- c. Autoignition of H_2 resulting from thermal cookoff
- d. Pyrophoric ignition of hydrogen due to metal-water reactions
- e. Hot jet ignition of hydrogen
- f. Shock heating
- g. Thermal explosion-initiating mechanisms

h. Flame

i. Ionizing radiation? Note: some explosives can be initiated when exposed to high concentrations of alpha particles

j. Piezoelectric effects

h. Pyroelectric effects.

These ignition mechanisms should be evaluated.

5. Issue: The chemical complexity of the organic/combustible mixtures resulting from a failure.

Resolution: The chemical composition of a mixture plays a dominant role in determining ignition potential and energy yield. For example, if helium is used as a diluent in an H_2-O_2 mixture, the detonation velocity can be enhanced. Therefore, the failure-release compositions and their variation in time must be evaluated.

6. Issue: The complexity of the mass transport and diffusion processes after failure.

Resolution: Investigate the many potential mass transport and diffusion processes in the HTGR-R system. Some include PV release, buoyancy, thermal transport, selective diffusional demixing, and deflagration transport.

7. Issue: The lack of evaluation of flammability behaviors for various mixtures of chemical species and concentration.

Resolution: There are an "infinite" number of flammability behaviors for various mixtures when the chemical species and concentration are varied. The application study considers only

a detonation behavior as it relates to the condensed-phase explosive, TNT. The flammability behaviors of various $H_2-CH_4-CO-CO_2-N_2-O_2$ systems must be investigated. Possibly, much of what we consider to be a problem may resolve to a nonproblem.

8. Issue: The nonideality of gas-phase explosions and the fallacy of TNT equivalency.

Resolution: With the exception of a sabotage event, all potential explosions within the HTGR-R system are nonideal explosions (e.g., confined fuel-air explosions, unconfined fuel-air explosions, pressure-volume explosions, and boiling liquid expansion vapor explosions). If one equates their energy yields to a condensed-phase explosive that is considered ideal, one has a misrepresentation that may either overestimate or underestimate the explosion hazard.

It is convenient to consider point source, nuclear, and high-explosive explosions as ideal explosions. Here, a point-source explosion is a mathematical idealization in which a quantity of energy is conceptually deposited in an infinitely short period of time at an infinitesimal point in space, and the equations of motion are solved to determine the nature of the blast wave that is produced. The reason why these three different sources can, for all practical purposes, be considered as "ideal" sources is that over the pressure range, from blast waves causing severe damage down to the acoustic level, these sources produce, to a very good approximation, identical blast waves. Furthermore, Sach's energy-scaling technique adequately correlates over-pressure and energy-scaled positive impulse for these sources in this pressure range. Above this pressure level, these sources do produce differences in the blast wave. However, when one is this close to the explosion source, damage is so severe that these differences are not important.

Virtually all other energy sources that produce a blast wave must be considered as nonideal sources. This is because the nature of the blast wave that is produced by these sources is affected by the behavior of the energy-release process in the source region.

It is well known that for ideal blast waves, the shock overpressure as well as the energy-scaled positive impulse of the wave are uniquely related to the energy-scaled radius of the source. It is also true that many combustion-generated accidental explosions involve a source region that is initially in the gas phase. The main difference between these explosions and the explosion generated by energy release from an "ideal" source is the very low energy per unit volume of the source region for such gaseous explosions.

For these reasons, one is ill-advised to use the concept of TNT equivalency. It would be sad indeed if the HTGR-R program were terminated because a decision-maker believed that there was the equivalent of 5800 lb of TNT in the HTGR reformer, or 22 million pounds TNT in the TCP stored-gas repository.

An alternate scheme to TNT equivalency is to develop the explosion scenarios upon a theoretical basis and document experimentally, adjusting the theoretical basis to model reality. Next, generate data in terms of a peak overpressure, energy-scaled impulse, and distance attenuation. Then, describe the blast effects in terms of distance.

9. Issue: The complex and unknown aspects of accidental explosion phenomenology.

Resolution: A very important fact for the designer of the HTGR-R to be aware of is that accidental explosions are exceedingly complex and no two explosions are identical. There are many

unknowns and the experimental data can possess large error bands. Therefore, we recommend that a considerable amount of effort (both theoretical and experimental) be directed toward the development of the design basis accidents.

10. Issue: The dynamic resistance function of the blast receiver.

Resolution: An explosion can produce a variety of effects, e.g., thermal, aerosolization, blast wave, or fragmentation. The vulnerability of the targets to be protected must be evaluated. If the HTGR-R containment shell were designed, built, and tested to contain 70 psig pressures, would a gas-phase explosion pressure of 90 psig fail it? Not necessarily; the explosion pressures are dynamic transients and their effects can be considerably different than that from a static load. Even using TNT overpressure and impulse data can produce gross errors due to the much longer durations of a gas-phase explosion. Also, the reflection histories for an accidental gas-phase explosion are much more complex than a condensed-phase explosion.

11. Issue: The requirements or conditions for a fire or an explosion to occur.

Resolution: Only by knowing the conditions under which a fire or an explosion can occur can we hope to prevent it. In general, there are four conditions that must be met for a fire or explosion of gaseous fuels to occur:

Condition 1. A combustible gas within a flammable or detonable concentration must be present within the system.

Condition 2. An oxidizer such as air (oxygen) must be in admixture or interface.

Condition 3. An initiation source (e.g., heat, shock, friction, spark, flame) must be present and at a minimum strength.

Condition 4. Chain carrier radicals (ions) must be produced within the flame front or the reaction zone which propagates the combustion reaction.

The elimination of any one of these four conditions within the system will prevent a fire or explosion. Most "fire- or explosion-control strategies" (FEDs) utilize equipment, materials, or conditions that interfere with one of these requirements. Examples of control strategies for consideration with the HTGR-R Program are:

FEDS 1. Water deluge--Condition 3: cooling, energy sink.

FEDS 2. Ventilation--Condition 1: reduction of fuel concentration.

FEDS 3. Wind transport--Condition 1: reduction of fuel concentration.

FEDS 4. Containment geometry (detonation traps, critical diameter, quenching gap in air, detonation induction distance)--Condition 3: energy depletion through rarefaction wave development, energy sinks, and elimination of turbulence generators in the flow field.

FEDS 5. Electrical conducting surfaces--Condition 3: elimination of charge buildup.

- FEDS 6. Shock mitigators--Condition 3: destructive interference, attenuation, and energy sinks.
- FEDS 7. Preferential diffusion--nondesirable augmentor of Conditions 1 and 2: not only is hydrogen more reactive, but its higher molecular diffusivity causes it to behave in another strange way. It has a very strong tendency to generate cellular flames or curve flamelets during flame propagation. The fuel molecule has a much higher diffusivity than the oxidizer molecule, and this leads to a phenomenon called preferential diffusion or selective diffusional demixing. The process generates cellular flame structures rather than normal laminar ones. It occurs not only in lean hydrogen-air mixtures but also in rich, heavy hydrocarbon-air mixtures.
- FEDS 8. Safety screens, e.g., Davey Lamp--Condition 3: cooling of flame through heat transport by conduction.
- FEDS 9. Inerting--Condition 2.
- FEDS 10. Dilution--Condition 1.
- FEDS 11. Water mist--Condition 1: dispersion, reduction of fuel concentration, and energy sink.
- FEDS 12. Class ABC extinguishment powder--Condition 4.
- FEDS 13. Explosion suppression systems (deflagration only)--Condition 4.

- FEDS 14. Explosion venting--Condition 3: reduction of energy yield through elimination of containment conditions and processes. This reduces shock-up or pressure piling.
- FEDS 15. Class D extinguishment powder--Condition 2: smothering.
- FEDS 16. Single, double, triple containment systems--Condition 2.
- FEDS 17. Ignitors and flare stacks--desirable augmentor of Condition 3: produces a controlled diffusion flame instead of a destructive premixed flame.
- FEDS 18. Limited release through flow restrictors or controlled volumes--controlling the energy yield by controlling the mass of fuel.
- FEDS 19. Elimination of turbulence generators from the flow field, e.g., screens, piping, stairwells, equipment racks--Condition 3: the energy yield is a function of flame velocity. Flame acceleration through interaction with a turbulence generator can increase the amount of energy that preconditions the fuel-oxidizer mixture.
- FEDS 20. Cooled fuel systems--Condition 3: chemical reactivities change with temperature.
- FEDS 21. Gas buoyancy--Conditions 1 and 2: buoyancy accounts for the 4.1% lower flammable limit of hydrogen. Buoyancy can change the explosion risks considerably, depending on whether it occurs before ignition or after ignition.

FEDS 22. Flammable limits of combustible fuels--Conditions 1 and 2: flammability limits must be used with great caution when designing a defensive strategy because they are an experimental value that is experiment dependent, for there is nothing in the laminar, adiabatic solution that generates such discontinuities. It is only for nonadiabatic systems and multidimensional solutions that finite limits can appear. There are various nonadiabatic processes that compete with the flame-propagation process and dissipate power from the combustion wave. They inevitably involve multidimensional considerations. Those competing processes quench propagation at a finite velocity. The competing processes are: (a) free, buoyant convection; (b) conductive-convective wall losses; (c) radiative losses; (d) selective diffusional demixing; and (e) flame stretch or flow-gradient losses. To date, there are a number of experiments (involving turbulence generators, or diluents) that demonstrate the combustion of various fuels below their stated lower flammable limits in air. Also, limiting the reliance upon flammability limits is the concentration variation with time due to various mass transport and diffusion processes.

FEDS 24. Maximum Experimental Safe Gap (MESG)--Condition 3: the maximum permissible clearance, between flat parallel steel surfaces, that prevents the propagation of dangerous flames or sparks through the gap.

12. Issue: Fire/explosion scenario effects upon the:

a. HTGR Inherent Safety Features

- (1) Helium coolant
- (2) Graphite core
- (3) Coated-particle fuel form
- (4) PCRV and associated liner.

b. HTGR Design Safety Features

- (1) Core auxiliary cooling system
- (2) Containment building
- (3) Containment atmosphere-cleanup system
- (4) Containment isolation system
- (5) Plant protection system
- (6) Reserve shutdown system
- (7) Liner cooling system.

c. HTGR-R Design Safety Features

- (1) Pressure relief system which prevents PCRV overpressurization by relieving excess pressure to the containment.
- (2) Automatic isolation of the secondary loops in response to low pressure or high radioactivity level.
- (3) Core auxiliary heat exchanger isolation system which detects conditions that indicate a leak between the CACWS and the primary coolant system.

Resolution: Critical evaluation documented in the safety analysis.

13. Issue: Reformer operation or the postulated fire/explosion scenario effects upon the previous NRC review issues:

- a. Design criteria for graphite structures
- b. Core seismic response
- c. Inservice inspection and training
- d. Preoperational vibration testing of reactor internals
- e. Anticipated transients without scram
- f. Confirmation of the Containment Design Basis
- g. Long-term behavior of metallic components of the primary coolant system
- h. Thermal-hydraulic phenomena during safe shutdown cooling
- i. Low-probability accident definition.

Resolution: Critical evaluation documented in the safety analysis.

Identified Safety Concerns Associated with
Organic/Combustible Material Interface with Personnel

A review of the applications study identified in the following safety concerns:

1. Issues and Resolution: Biological toxicity. All toxic species must be identified, their release and dispersion scenarios (concentration, distance, time) established, and interaction effects on personnel described. Carbon monoxide and nickel carbonyl appear to be the most severe agents. It is advised that protective distances be stated in terms of the threshold limit values (the safe concentration a person can be exposed to for an eight-hour day and a 40-hour week without adverse effect) rather than lethal effects. Also, the impact of sublethal concentrations on operations personnel and this effect upon plant safety need to be addressed.
2. Issue and Resolution: Asphyxiation. Agents such as CH_4 , CO_2 , H_2 , N_2 , He, and water vapor need to be identified and addressed as in Item 1.
3. Issue and Resolution: Fire. Effects upon personnel and plant operations need to be addressed.
4. Issue and Resolution: Explosion. Effects upon personnel and plant operations (as it relates to human factors) need to be addressed.

DISCUSSION OF THE NATURE OF ACCIDENTAL EXPLOSION ANALYSIS AND ITS IMPACT UPON HTGR-R DEVELOPMENT

At this stage of the development, it appears that the major concerns of the HTGR-R concept, as it relates to operational safety and the licensing process, are accidental explosions and toxic exposure to personnel. Perhaps a better understanding of accidental explosions would assist in the search for solutions to the problem.

For point-source explosions, where a known amount of stored energy is released in a short period of time (μ s) from a single location, the resulting overpressures, impulse, and blast effects of the shock wave can be accurately predicted. A detonation involving dynamite is an example.

For accidental gas-phase explosions, the deflagration-detonation processes are much more complex and subject to change due to alterations in various parameters, such as density; mixing; layering; ignition strength, location, and source; geometry; adiabatic process; and reflections. Therefore, in accidental gas-phase explosions, the rate of energy release is extremely variable. As a result, the point-source explosion theory proves inadequate.

The general concept of TNT equivalence for these nonideal explosions is not well understood at the present time. It is true that usually near-field overpressures are much less than that of a point-source explosion which produces the equivalent far-field overpressure, but neither the exact relationship between near-field and far-field behavior nor how this relationship changes as the type of accidental explosion changes is obvious. Also, it is not obvious how one should evaluate the effectiveness for blast damage of any particular type of accidental explosion or how much the effectiveness depends on type.

Three approaches to TNT equivalency have been used to date. The first and most practical approach is an a posteriori approach involving real

accidents. After an accident, the blast-damage pattern is used to determine the weight of TNT that would be required to do the observed amount of damage at that distance from the center of the explosion.

The second approach is to deliberately initiate a nonideal explosion and measure side-on blast pressures. The maximum TNT equivalent yield of the explosive is calculated on the basis of empirical formulas and the percent yield in terms of the two variables, overpressure and positive impulse, are plotted versus a scaled distance.

The third approach is an a priori approach and involves the calculation of the source energy which is available to the blast wave. However, to date, there has been no proof that this is the correct way to evaluate the maximum available yield for an accidental explosion.

Generally, accidental explosive systems do not compare with designed explosive systems in either energy density, reaction rate, or total yield; but, in terms of low activation energies and initiation sensitivity, the hazards are greatly reversed. Most accidental explosions produce lower amplitudes (overpressures) and longer-duration energy flows (impulse).

For added information on explosion phenomenology, see Appendix A.

A general explosion analysis of the HTGR-R system (HTGR, Reformer, Gas Storage TCP, Methanator) was conducted using the following information:

1. MORT Logic, Figures 1-4
2. HTGR-R Characterization Tree, Figure 8
3. Systems Analysis for Explosions Hazard, Figure 9
4. Explosion Phenomenology, Appendix A.

Figure 8. HTGR Characterization Tree.

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Figure 8. HTGR Characterization Tree (cont.)

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Figure 9. System analysis for explosion hazards

Figure 9. System analysis for explosion hazards (cont.)

Figure 9. System analysis for explosion hazards (cont.)

Figure 9. System analysis for explosion hazards (cont.)

* Indicates applicability to HTGR-R

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Figure 9. System analysis for explosion hazards (cont.)

It was determined that seven distinct classes of explosion scenarios should be considered:

1. Confined fuel-air explosions (CFAE)
2. Unconfined fuel-air explosions (UFAE)
3. Pressure-volume explosions (PV)
4. Boiling liquid expansion vapor explosions (BLEVE)
5. Physical vapor explosions (PVE)
6. Thermal explosions (TE)
7. Sabotage explosions (SABO).

Each of these explosion classes, for any given HTGR-R scenario, can differ considerably with regard to the following variables:

1. Size of the explosion-source region
2. Total energy yield
3. Energy density
4. Energy-partitioning mechanisms
5. Overpressure
6. Impulse
7. Reflected shock production
8. Thermal effects

9. Near- and far-field effects
10. Radius of action
11. Target effects, including personnel effects
12. Ability to trigger post-explosion events
13. Ability to aerosolize radioactive materials.

Also, it should be noted that the technical options for defending against these classes vary.

To develop valid explosion scenarios upon which a defense can be established, one must assess a multitude of factors: system descriptors, failure events, and their cause-consequence. Figure 10 provides a generic description of these factors.

To demonstrate the complex nature of scenario development, it may be instructive to cite the kind of scenario input information required for a confined fuel (H_2)-air explosion within the containment of a pressurized water reactor (PWR) system. To establish either the theoretical worst case or the most likely PWR containment hydrogen explosion scenario and its consequence, seven recognized process phases must be analyzed:

1. Phase 1 deals with hydrogen-gas generation within the reactor system during the LOCA. Vital input to the explosion analysis is how much hydrogen is produced and how fast. Critical parameters affecting this input are core temperature, the amount of zirconium reacting, change in surface area with time, heats of reaction, shock production, mass and heat transport, oxide production and interaction, other competing reactions such as $Zr + Ni @ 1750^\circ F$, gas solubility in water, and structural changes in the core with time.

Figure 10. Explosion Scenario Events and Casual Factors Charting Tree.

2. Phase 2 involves the transport of hydrogen gas through the reactor system. Vital input to an explosion analysis is how much hydrogen is transported, how fast, and to what location. Different transport mechanisms, i.e., two-phase flow, large gas bubble transport, can significantly affect the mass transport rate and how the gas is partitioned to different parts of the reactor system.
3. Phase 3 involves the effluxing of hydrogen gas from release points in the reactor system. Critical factors affecting this phase are pressure transients within the system, the size of potential openings, distances and elevations from the gas-production zone, and the dynamic resistance function of seals, valves, flanges, and welds.
4. Phase 4 involves the hydrogen gas plume production within the PWR containment. Critical factors affecting this phase are hydrogen pressure, release-point orifice size, amount of hydrogen released, release rate, turbulence, gas buoyancy, diffusion, effluxing of water, and gas solubility.
5. Phase 5 deals with the ignition mechanisms that could ignite the hydrogen plume. The type, strength, location, and time duration of the ignition source all significantly influence whether or not a combustion event will occur and how severe it will be.
6. Phase 6 deals with the mode of hydrogen-air combustion within the PWR containment. There are many modes of combustion possible, all of which produce different energy yields at different distances. Diffusion flame combustion, for instance, rarely produces significant pressure pulses, while deflagrations may produce pressure ratios of 8:1. Detonations, on the other hand, may produce pressure ratios in excess of 40:1. The type of combustion mode produced in an accident situation is a function of many variables, some of which are listed below:

- a. Concentration of fuel and oxidizer and degree of admixture
 - b. Type and strength of ignition source
 - c. Geometry of the gas-confinement system
 - d. Presence of heat sinks such as water vapor
 - e. Flame-acceleration mechanisms such as Taylor instability, or turbulence generators within the flow field.
 - f. Chain carrier radical (active ions) production or depletion within the flame front.
7. Phase 7 deals with the effects on the target (containment building) and requires a knowledge of the dynamic-resistance function of the structure. The dynamic resistance of the structure is a function of the pressure-time history of the driving force.

Below, are specific examples of the seven explosion classes, as they relate to the HTGR-R system:

1. Steps of an HTGR-R Containment (confined fuel-air) Explosion are:
 - a. Reactor transient (X) occurs.
 - b. Pressure imbalance occurs between primary and secondary side of direct-cycle reformer (IHx) and subjects IHx to sudden pressure load.
 - c. Dynamic yield strength of IHx reformer and cavity liner is exceeded and rupture occurs venting combustible gases to the PCRV.

- d. PCRV pressure-relief system (HTGR-R safety feature) vents combustible gases to the containment.
 - e. Gas-plume production occurs.
 - f. Admixture with air occurs.
 - g. Soft ignition occurs.
 - h. A slow-combustion mode occurs.
 - i. Flame-acceleration processes occur which produce combustion-velocity transition, i.e., deflagration, deflagration-detonation transition.
 - j. Reflections occur producing constructive or destructive interference. Blast waves are produced of some amplitude and duration. Aerosolization occurs.
 - k. Blast wave reinforcement or attenuation occurs.
 - l. Blast wave loads containment structure through reflection phase. Multiple reflections occur in containment.
 - m. Containment responses to loading.
 - n. The Nuclear Process Heat Source (NPHS) and Process Plant and Delivery System (PPDS) respond to the explosion transient.
2. Steps of an HTGR-R Unconfined Fuel-Air Explosion are:
- a. A transient occurs in the Process Plant and Delivery System which results in a failure and X tons of combustible material being released to the environment.

- b. Mass transport and diffusion processes occur which move the cloud from the point of release.
 - c. Admixture with air occurs producing a plume of variable size and concentration.
 - d. Cloud-environment interaction occurs (consider structures, terrain, equipment, personnel, meteorological conditions, etc.) which results in an explosion-source region of some size and concentration.
 - e. Soft ignition occurs.
 - f. A slow-combustion mode occurs.
 - g. Flame acceleration occurs.
 - h. A high-order deflagration is established.
 - i. Structures, equipment, and personnel, respond to loading.
 - j. The NPHS and PPDS responds to the explosion transient.
3. Steps of an HTGR Pressure Volume Explosion are:
- a. A failure occurs in the wall of the thermochemical pipeline (TCP) due to corrosion.
 - b. A fracture is produced in the wall due to the pressure-volume (PV) energy of the compressed gases.
 - c. A propagating oscillatory fracture is established because the crack-propagation velocity exceeds the PV energy-equilibration rate. Potentially, many miles of pipe could be affected.

- d. The PV energy release results in the production of shock waves for as far as the crack propagates.

NOTE: Ignition is not assumed, although it is highly likely through the Inverse Joule-Thompson effect. Ignition would produce an unconfined fuel-air explosion.

4. HTGR-R Boiling Liquid Expansion Vapor Explosion (BLEVE):

When a container of high vapor-pressure fuel is ruptured because of an external fire, the contents burn immediately and produce a tremendous fireball, which results in very little blast damage and rocketing pieces of the container. This type of explosion is called a BLEVE. Considering the large amounts of methane stored in the gas-storage field of the Process Plant and Delivery System, it appears cryogenic techniques may be employed. Containers of LNG are vulnerable to this explosion mechanism.

5. HTGR-R Physical Vapor Explosion:

Many fluids are stored in vessels under sufficient pressure that they remain essentially liquid at the vapor pressure corresponding to the storage or operating temperature for the particular liquid. Examples are propane or butane fuels which are normally stored at "room" temperature; methane (LNG) which must be stored at cryogenic temperatures; refrigerants, such as ammonia or the Freons, which are also stored at room temperature; and boiler drums. If a vessel containing such fluids fails, the resulting sudden pressure release can cause expansion of vapor and partial flash evaporation of the liquid, and drive a blast wave into the surrounding air. There appears to be this kind of potential in the gas-storage system. Also, water ingress into areas of the PCRVR may produce a steam flash.

6. HTGR-R Adiabatic Thermal Explosion:

Any chemical system that is undergoing a homogeneous exothermic chemical reaction, if physically isolated from the surroundings, will eventually explode. Physical isolation means under some condition of confinement with inadequate provisions for dissipating the heat of reaction. The reformer and the methanator systems appear potential targets for this explosion mechanism if:

- a. Faults occur in the circulating pumps or heat-transfer systems
- b. Chemical-reaction kinetics are altered through changes in chemical composition of feed material, catalysis, pressure, or temperature.

7. HTGR-R Sabotage Explosion:

Any system that utilizes, stores, or transmits large amounts of energy or energy-bearing materials should be assessed for vulnerability from sabotage. It is possible that a minor sabotage event could trigger a major energy release.

Accidental fire and explosion potential can be controlled, within limits, through the implementation of various Fire and Explosion Defensive Strategies (FEDS). Limits to consider are accident risk (probability x consequences), state of technology, time, material, and financial resources. A defensive strategy may involve either software or hardware, or both, and should provide some form of barrier during at least one of the following defensive stages of an accident:

1. Prevention Stage: A pre-accident planning stage that is characterized by the development of designs, analyses, programs, procedures, construction, and checkout of FEDS hardware.

2. Mitigation Stage: This stage occurs during the energy flow of the accident and involves the action of hardware that will absorb, attenuate, redirect, or recondition the energy flow, i.e., interact with the energy flow and defend the target.
3. Amelioration Stage: This stage is post-accident (after the energy flow) and involves prevention of a second accident, emergency actions, rescue, medical services, rehabilitation, and public relations.

There appears to be many defensive strategies that could be applied to the HTGR-R system, but a precise description is not possible due to the dependency upon unavailable information including system structure, process function, fault-failure analysis, and potential hazard recognition. Certainly, the following general strategies would apply:

1. Conduct fault-failure analyses.
2. Control fault failures.
3. Control the requirements for fire/explosion to occur, e.g., reducing agents, oxidizing agents, initiating heat, reaction chain carrier ions.
4. Understand explosion phenomenology.
5. Define plant accident conditions and scenarios and the limiting system/component loading conditions.
6. Conduct accident initiation and progression analysis analyses.
7. Develop valid fire/explosion scenarios based upon both theoretical and experimental evidence.

8. Conduct theoretical and experimental analyses of the scenarios, scoping model tests and Buckingham Pi Scale Modeling.
9. Evaluate all potential FEDS.
10. Model the HTGR-R system and the FEDS.

A listing of possible Fire and Explosion Defensive Strategies for the HTGR-R Systems is described as follows:

1. Software Techniques:

- a. Fault-Tree Analysis (FTA)
- b. Cause-Consequence Analysis (CCA)
- c. Safety Analysis (SA, SAD, PSAR, FSAR)
- d. Historical Accident Analysis (HAA)
- e. Accident Initiation and Progression Analysis (AIPA)
- f. Facility characterization
- g. Systems analysis for explosion hazards
- h. Systems safety and risk assessment technology
- i. Procedures
- j. Target Vulnerability Analysis
- k. Structural Materials Analysis

1. Process Materials Analysis
 - m. Knowledge of flammability behavior
 - n. Independent review.
2. Hardware Techniques:
 - a. Water mist diffusion of flammable vapors
 - b. Water sprinklers
 - c. Water-deluge systems
 - d. Ventilation
 - e. Process containment
 - f. Mass transport and diffusion (knowledge of mechanisms)
 - g. Detonation traps
 - h. Containment geometry
 - i. Critical diameter (knowledge of and control)
 - j. Quenching gap in air (knowledge of and control)
 - k. Detonation induction distance (knowledge of and control)
 - l. Electrical conducting surfaces
 - m. Shock mitigators (absorbers, barriers, reflectors)

- n. Preferential diffusion (knowledge of and control)
- o. Inerting
- p. Dilution
- q. Screens (thermal sinks)
- r. Extinguishing materials, Class A, B, C, D
- s. Explosion-suppression systems
- t. Explosion venting
- u. Ignitors
- v. Flare stacks
- w. Material flow restrictors
- x. Turbulence generators (control of)
- y. Autoignition temperature (knowledge and control of)
- z. Refrigerated systems
- aa. Gas buoyancy (knowledge of and control)
- bb. Flammable limits (knowledge of and control)
- cc. Maximum experimental safe gap (knowledge of and control)
- dd. Scoping model tests

ee. Buckingham Pi Scale Modeling

ff. Heat sinks

gg. Explosion containment.

A REVIEW OF RELEVANT SAFETY AND LICENSING APPROACHES USED
IN NUCLEAR PROCESS HEAT APPLICATIONS AND IN THE SYNFUELS INDUSTRY

Little information was found, within the time frame for publication of this document, that directly addressed the relevant safety and licensing approaches used in nuclear process heat applications. It appears obvious that any licensing document that exists would require controls (e.g., detectors and protection systems) and isotope-concentration limits for cross-contamination of process heat fluids by the nuclear heat source.

Control in the synfuels industry would appear to be the same (licensing, operational compliance, etc.) as that of the petroleum industry. Certainly, the Department of Transportation regulations and the recommendations of the National Fire Protection Association and the American Petroleum Institute appear relevant.

The most relevant safety approach would be one of system safety, based upon the Management Oversight Risk Tree concepts, due to the fact that it is the system used by the Department of Energy and the Nuclear Regulatory Commission.

CONCLUSIONS AND RECOMMENDATIONS

1. The HTGR-R concept appears to be worthy of continued support.
2. The needs of three categories of readership should be satisfied:
 - a. The HTGR Program participants who must agree upon an HTGR design and focus upon a development effort.
 - b. The licensing and safety personnel who must review the document and render opinions based upon what they read.
 - c. The funding organizations who must be convinced that the program warrants the financial and technical support and effort.
3. A review of the document raises the following safety-related issues that should be addressed in ongoing safety work:
 - a. Questions concerning structural material properties under the stated process conditions, e.g., pressure, temperature, material interface, or nuclear environment.
 - b. The initiating causes and consequences of combustible materials contacting nuclear materials.
 - c. The initiating causes and consequences of combustible materials admixing with air or other oxidizers.
 - d. The design barriers limiting the admixture of materials described in Items b and c above.
 - e. Nuclear reactor anomalies and their interaction effects upon reformer function.

- f. Anomalous behavior of the reformer and its interaction effects upon reactor function.
 - g. Potential toxic and explosion interaction effects upon personnel.
4. The credibility of the applications study appears to be primarily based upon theoretical and engineering design calculation. We believe that an experimental and statistical basis should be strongly developed.
 5. We believe that unresolved safety issues, and their relationship to the licensing process, could severely inhibit the development program. To prevent this happening, we recommend the Management Oversight Management Tree methodology systems safety approach be used to identify the inherent risks, suggest methods of risk reduction, and produce an acceptable program.
 6. Definition of plant-accident scenarios and the limiting system/component-loading conditions must be established as soon as possible as these are critical to establishing the plant safety goals and the available design approaches to defend against the unique HTGR-R hazard events.
 7. TNT equivalency should be avoided in estimating the potential explosion effects of any HTGR-R accident. Blast damages should be analyzed according to the particular mode of combustion or energy-release mechanisms that occurs within the explosion-source region, e.g., gas cloud or volume. The simple analytical Brinkley-Kirkwood theory provides a valuable tool to estimate blast damage, if one assumes that the blast energies are about 20% and 25% of the total combustion energy of the mixture for fuel-air and fuel-oxygen detonations, respectively.

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APPENDIX A
EXPLOSION PHENOMENOLOGY

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APPENDIX A
EXPLOSION PHENOMENOLOGY

DEFINITION OF EXPLOSION

In general, an explosion is said to have occurred in the atmosphere if energy is released over a sufficiently small time and in a sufficiently small volume, so as to generate a pressure wave of finite amplitude traveling away from the source. This energy may have been originally stored in the system in a variety of forms, e.g., nuclear, chemical, electrical, or pressure energy. However, the release is not considered to be explosive unless it is rapid enough and concentrated enough to produce a pressure wave that can be heard.

SYSTEMS ANALYSIS OF THE EXPLOSION ENVIRONMENT

When an explosion occurs, its characterization can be thought of as an event involving three broad concepts:

1. The donor system (the description of the material that produces explosive output)
2. The receiver system (personnel, equipment, or "acceptor" explosives) which requires a level of protection
3. The protective system which shields against or attenuates the hazardous effects to levels tolerable to the receiver system.

DONOR SYSTEMS

Types

There are three fundamental types of explosion donor systems: nuclear, mechanical, and chemical. Nuclear explosions can be subdivided into fission and fusion systems. Mechanical explosions can be subdivided into two systems: the molecular and the binary (redox). The molecular system is characterized by the presence of an intrinsically unstable molecule and an initiating agent. The molecules can react in special ways, such as oxidation-reduction, decomposition, or polymerization reactions. The binary (redox) system requires four components, very similar to the fire rectangle: an oxidizing agent, such as oxygen; a reducing agent or fuel; an initiating agent, such as friction, heat, shock, or spark; and chain carrier ions that propagate the reaction.

Initiating Agents

There are many known initiating agents, many of which have been discovered accidentally. Basically, they do the same thing--provide heat activation energy. Examples of known initiating agents are: impact, shock, direct heating, adiabatic heating of compressed-gas spaces, frictional hot spots, intercrystalline friction, viscous heating of sharp points when deformed plastically, mutual reinforcement of gentle shock waves, vibrations, electrons, neutrons, fission fragments, intense light, electric discharge, and spontaneous initiation of growing crystals.

Sensitivity

The sensitivity and manner of initiation is dependent on chemical characteristics of the explosive, physical form, aeration, temperature, degree of compression, particle form and size, moisture content, impurity content, density, type and size of containment, and the degree of confinement.

Explosion Process

There are many types of processes that lead to explosions in the atmosphere. Table A-1 contains a comprehensive listing of some types, including theoretical models, natural explosions, intentional explosions, and accidental explosions. The list in the table is by type of energy release.

General Characteristics of Explosions

Energy and its distribution change with time as the pressure wave propagates away from the source and are important properties in determining the behavior of the explosion process. Initially, all the energy is stored in the source in the form of potential energy. At the instant when the explosion starts, this potential energy is redistributed to produce kinetic and potential energy in different parts of the system. Figure A-1 describes the energy distribution in a blast wave.

The violent release of energy from an explosion in a gaseous medium gives rise to a sudden pressure increase in that medium. The pressure disturbance, termed the blast wave, is characterized by an almost instantaneous rise from ambient pressure to a peak incident pressure (P_{so}). This pressure increase or shock front travels radially away from the burst point with a diminishing velocity (V) which is always in excess of the sonic velocity of the medium. Gas molecules, making up the front, move at lower velocities (v). This velocity is associated with a dynamic pressure (q) or the pressure formed by the winds produced by the shock fronts. As the shock front expands into increasingly larger volumes of the medium, the peak incident pressure at the front increases and the duration of the pressures increases.

At any point away from the burst, the pressure disturbance has the shape shown in Figure A-2. The shock front arrives at time, t_A , and, after the rise to the peak value, the incident pressure decays to the

TABLE A-1. EXPLOSION TYPES

Theoretical Models	Natural Explosions	Intentional Explosions	Accidental Explosions
Ideal point source	Lightning	Nuclear explosions	Pressure vessels
Ideal gas	Volcanoes	High explosives	Simple failure (no combustion)
Real gas	Meteors	Blasting	Runaway chemical detonation before failure
Self-similar (∞ source energy)		Military	
Constant velocity piston		Pyrotechnic separators	Internal explosion or detonation before failure
Accelerating piston		Guns	
		Muzzle blast	
Bursting sphere		Recoilless rifle	Failure followed by immediate combustion
Finite stroke piston		Exploding spark	
Detonation driven		Exploding wires	Gaseous explosions in enclosures (e.g., buildings, cars)
		Laser sparks	
		Continuous source ^a	Unconfined vapor cloud explosions
		Contained explosions ^b	High explosives and propellants during manufacture, transport, storage, or use
			Physical explosions
			Nuclear reactor runaway
			Laboratory explosions

a. Hypervelocity missile and supersonic aircraft are examples.

b. Contained vessel explosions and automotive knock are examples.

Figure A-1. Energy distribution in a blast wave as a function of time after the explosion (schematic).

Figure A-2. Ideal blast wave structure.

ambient value in the time, $t_A + T^+$, which is the positive phase duration. This is followed by a negative phase with a duration, T^- , longer than the positive phase and characterized by a pressure below the preshot ambient pressure and a reversal of the particle flow. The negative phase is usually less important in design or safety. The incident impulse associated with the blast wave is the integrated area under the pressure-time curve and is denoted as i_s for the positive phase and i_s^- for the negative phase.

If the shock wave impinges on a rigid surface oriented at an angle to the direction of propagation of the wave, a reflected pressure (P_r), is instantly developed on the surface, and the pressure is raised to a value of 2 to 8 times. Some receivers are sensitive to P_{s0} , others to i_s .

Other explosion effects are primary and secondary fragments, including fire, heat, dust, ground shock, and toxic products. These also can produce adverse effects on receivers, thereby requiring a protective system.

Hazard Explosion Reactions

Chemical explosions are those in which a chemical reaction is the source of the high-pressure gas. It is convenient to divide chemical reactions into three types for the purpose of discussing their hazard potential.

Uniform Reactions

Uniform reactions are those in which the reaction occurs more or less uniformly throughout the mass of material. Ordinary chemical reactions, which form gaseous products at a rate faster than they can be vented, fall into this category. Exothermic reactions performed under conditions of confinement with inadequate provisions for dissipating the heat of reaction can accelerate to the point where high-pressure gases are generated and a thermal explosion ensues.

Propagating Reactions

Propagating reactions are those in which the reaction initiates at a specific point in the material and propagates from that point as a reaction front through the unreacted material. In all cases, the reaction front presents a sharp discontinuity in concentration and temperature. In some cases, a sharp discontinuity in pressure also occurs at the reaction front. For a propagating reaction to continue at a steady-state condition, energy from the reaction zone must reach the unreacted material. Propagating reactions are, therefore, divided into two classes depending on the mechanism for energy transfer.

1. Deflagrations are propagating reactions in which the energy transfer from the reaction zone to the unreacted zone is accomplished through ordinary transport processes, such as heat and mass transfer. Examples of deflagrations are flames and combustion processes in which heat, free radicals, and atoms diffuse from the reaction in each successive increment of reactant. The rates of such reactions are thus controlled by the rate of the particular transport phenomenon being applied.
2. Detonations, on the other hand, are propagating reactions in which energy is transferred from the reaction zone to the unreacted zone on a reactive shock wave. The velocity of such reactions always exceeds the local velocity of sound in the reactant. Detonation velocity is given by the expression:

$$\text{Detonation velocity} = \text{velocity of sound} + \text{velocity of mass}$$

The manner in which the difference between deflagration and detonation manifests itself as pressure, developed in each specific case, is important to the analysis of the damage potential of a chemical reaction.

A deflagration once initiated can transform into a detonation with much higher damage potential. In order to assess the damage potential of materials, a knowledge of their tendency to deflagrate or detonate must be known.

Fire Reactions

Fires, due to their nature, must be included in explosion reactions because of five important reasons:

1. Fires are a deflagration process and their reaction rates can change drastically; the rate doubles with approximately every 9°C (17°F) change in temperature.
2. Fires may provide the "parent event" for post-fire explosions by contributing the fuel and initiation source, or by producing physical and/or chemical changes in adjacent compounds or components.
3. Fires provide the major damage mechanism for most industrial explosions.
4. Almost all chemical explosives (one notable exception being lead azide) begin their explosive reaction by deflagration, then transform to a detonation process. This is known as the deflagration/detonation transition (DDT).
5. Fires can sensitize receptor materials to explosion effects, thereby producing more damage than the explosion would have singularly.

Fires can occur only with the presence of: (a) fuel, (b) oxygen or other oxidizing agents, (c) sufficiently high temperatures to maintain combustion, and (d) ionized free radicals or "chain carriers." Elimination of a fire hazard and extinguishment can be accomplished by excluding any one of these four factors.

TNT Blast Standards and Accidental Explosions

The magnitude of an explosion is established by the amount and rate of energy released. This may be expressed directly in energy units, e.g., calories; but, a relative, rather than an absolute, measure for explosion size may be more meaningful and practical. This requires that some standard be defined. A generally accepted standard is the energy released by the explosion of TNT (symmetrical trinitrotoluene), selected as a standard because chemically pure material is readily available for calibration purposes, it is relatively safe to handle, and it gives reproducible explosive effects. By measurements of the energy in its blast wave, it has been determined that the explosion of 1 g of TNT, at a density of 1.5 gm/cm, generates a blast energy of about 1120 calories.

With regard to both laboratory and field tests, there is always some uncertainty in the measured values, even for calibrated blast waves as generated by standard TNT. This situation has led to the acceptance of an arbitrary standard for blast waves--the defined ton of TNT. This corresponds to an explosive energy release of 1 million kilocalories. An energy release of this amount represents $(10^6 \times 10^3 \div 2000 \times 454)$ 1100 calories per gram of TNT, which is in approximate agreement with average experimental values.

Because TNT is a commonly accepted standard, considerable empirical and theoretical data have accumulated which relate the quantity of explosive to blast parameters, such as peak overpressure, reflected pressures, impulse, and other blast effects. It must be recognized that accidental (non-ideal) explosions do not scale well to a TNT standard, and that the use of TNT equivalency can result in gross errors. To date, a standard for accidental explosion does not exist. Therefore, each potential accidental explosion should be evaluated through both a theoretical and experimental program.

GENERATION OF BLAST WAVES

As of 1979, there were four recognized processes that can possibly lead to excessive acceleration of flame and, therefore, the possible generation of destructive blast waves. These are:

1. A Taylor instability due to dynamic flow-acceleration processes: Classical Taylor instability occurs when a contact surface separating a light and a heavy fluid is accelerated in the direction of the lighter fluid. In contrast, a contact surface is stable and remains flat in the case when the acceleration is in the direction of the heavy fluid (for example, a normal water-air interface in the earth's gravity field). However, when the acceleration vector is reversed and held constant, the surface develops waves, the amplitude of which initially increases exponentially with time.

A premixed gas flame propagating through a fuel-air mixture is a relatively low velocity wave which produces a large density difference in the gas. In this case, the burned gases are approximately 6 to 8 times less dense than the unburned gas ahead of the flame. If such a flame and the fluid it is processing are impulsively accelerated by some external gas dynamic process in such a direction that the cool reactive gases are caused to push the hot product gases, the Taylor instability mechanism will cause the flame surface area to increase markedly. If the acceleration is sufficiently rapid, this rate of increase of flame area can be dramatic, and since the overall rate of conversion of reactants to products is directly proportional to the flame area, the effective burning velocity will increase markedly. The fact that Taylor instability causes flame-front convolution has been demonstrated in many investigations.

2. Turbulence generators being present in the flow system: There are two major types of turbulence generators in the flow that the flame passes through. The first of these is due to boundary-layer growth on interior surfaces. Pressure waves generated by the flame cause flow ahead of the flame, and this flow interacts with surfaces to produce a boundary layer which becomes turbulent if the flow velocity is high. Under these circumstances, the flame will start to propagate in this boundary layer at a higher velocity than the bulk space velocity, causing the generation of oblique flame sheets which increases the flame-propagation rate. When this happens, the rate of pressure rise inside the enclosure increases.

The experimental work of Utriw et al. (1965) and Utriw and Oppenheim (1967), discussed by Adamszyk and Strehlow,^{A-1,A-2,A-3} on the transition to detonation in hydrogen-oxygen mixtures shows that just before the detonation is formed, the flame takes on a conical shape whose leading edge is traveling down the wall boundary layer at a very high velocity. In this case, the flame area is extremely large compared to the frontal area of the tube, and the rate of pressure rise due to the flame propagation is extremely rapid compared to the initial rate of pressure rise in the system.

The effect of obstacles in the flow ahead of the flame is more difficult to evaluate. If flame propagation forces the flow to go through the obstacle region at high velocity, very-high-turbulence levels can be generated. Unfortunately, there has been very little experimental work on situations where the flame encounters a free-standing obstacle such as a piece of process equipment or a pipe rack either in a building or in the open.

3. Processes that involve the turbulent mixing of hot gas products with the cold unburned fuel-air mixture: Knystautas et al.

(1979), as discussed in Reference A-2, have discovered a new mechanism for the dynamic generation of a detonation wave which is pertinent to the accidental-explosion problem. Specifically, they discovered that the proper venting of a jet produced by a combustion process occurring in an enclosure can condition the gas in the external region in such a manner that a detonation is initiated without the presence of strong shock waves. In their experiments, a flame is propagated in an enclosure and produces a jet in the surrounding combustible media. This jet initially consists of cold combustible gas which is mixed with outside combustible gas. After some time, the flame reaches the orifice and, from that time on, hot combustion products are jetted out of the orifice into the surrounding media. For this process to occur, the shear in the jet region must be sufficient to cause extinguishment of the flame so that only hot products and cold reactants are present.

4. Direct shock heating: There is a large variety of geometries in which the flame-propagation process either causes an isentropic compression of the gas ahead of the flame or causes the generation of a shock wave ahead of the flame. In either of these cases, the pressure and temperature ahead of the flame are increased by the compression process. The question arises as to whether this bulk compression process, by itself, can cause sufficient flame acceleration to lead to direct transition to detonation.

It is known that damaging blast waves are not produced until effective flame velocities in the source region reach Lagrangian Mach numbers of above 0.25. In fuel-air mixtures, this corresponds to an effective flame velocity of about 80 m/s which is over 100 times the normal burning velocity of most stoichiometric hydrocarbon-air mixtures.

In virtually all accident explosion situations involving unconfined flames, ignition is effected by some type of "soft" ignition source (for example, a hot engine manifold, a spark from a motor housing, or a furnace that ingests the mixture). Thus, during an accidental-explosion sequence, the first thing that occurs after ignition is the spread of an extended fire. In this case, the flame is propagating through the mixture both as a diffusion flame in some regions and as a premixed flame in other regions. The only situation that is really dangerous, in the sense that a blast wave can be produced, is when there is a sufficient amount of mixture, within the flammable range, such that an extensive premixed flame can propagate through the mixture. This is because diffusion processes are generally so slow that a real explosive release of energy cannot occur if only diffusion flames are propagating.

Since we have already seen that relatively high effective flame velocities must occur before a dangerous blast wave can be produced, and since direct initiation of detonation is generally ruled out in an accident situation involving the ignition of combustible gases, the question of flame-acceleration processes becomes of paramount importance. Unfortunately, at the present time the description of flame-acceleration processes must be based entirely on experimental evidence. There is very little theory available, of a sufficiently sound physical basis, to augment observations.

An explosion is said to occur when either the rate of pressure rise or the rate of release of pressure is sufficiently fast that a finite amplitude pressure wave is propagated away from the source region. The nature of these pressure waves for "ideal" and "nonideal" sources will now be discussed in more detail.

It is convenient to consider point-source, nuclear, and high-explosive explosions as ideal explosions. Here, a point-source explosion is a mathematical idealization in which a quantity of energy is conceptually deposited in an infinitely short period of time at an infinitesimal point in

space, and the equations of motion are solved to determine the nature of the blast wave produced. The reason why these different sources can, for all practical purposes, be considered as ideal is that over the pressure range, where the blast wave causes severe damage down to the acoustic level, these sources produce a very good approximation of identical waves. Furthermore, Sach's energy-scaling technique adequately correlates over-pressure and energy-scaled positive impulse for these sources in this pressure range. Above this pressure level, these sources produce differences in the blast wave. However, when one is this close to the explosion source, damage is so severe that these differences are not important.

Virtually all other energy sources that produce a blast wave must be considered as nonideal sources. This is because the nature of the blast wave produced by these sources is affected by the behavior of the energy-release process in the source region. While it is true that nonideal source regions can have an infinite variety of behaviors that produce an infinite variety of blast waves, recent work by Strehlow and his co-workers [Strehlow and Ricker (1976), Adamszvk (1975), Luckritz (1977), Shimpi (1978)], as discussed by Baker,^{A-4,A-5} indicates that some generalizations can be made as to how nonideal source behaviors cause specific nonideal blast wave behaviors.

It is well known that for ideal blast waves, the shock overpressure, as well as the energy-scaled positive impulse of the wave, is uniquely related to the energy-scaled radius of the source. It is also true that many combustion-generated accidental explosions involve a source region that is initially in the gas phase. The main difference between these explosions and the explosion generated by energy released from an ideal source is the very low energy per unit volume of the source region for such gaseous explosions.

Because of the importance of these low-energy density explosions to accident situations, Strehlow and his co-workers have performed numerous calculations of the blast wave flow field associated with a large variety

of energy deposition types in spherical source regions of low-energy density. They have shown that, in general, two primary properties of these source regions can be used to describe the nonideality of the blast wave produced. The first of these important source region variables is the energy density of the source. Specifically, the energy density, q , is defined as the total amount of energy, Q , that is being added to the source region during the explosion, divided by the total internal energy of the source region at ambient pressure before the energy is added:

$$q = \frac{Q}{nC_v T} \quad (1)$$

In the denominator, n is the number of moles of gas present in the system, C_v is the heat capacity per mole, and T is the initial temperature of the mixture.

The second quantity of importance to nonideal behavior is the time it takes to add the energy to the source region. The proper way to nondimensionalize this time is to divide it by the time it takes a sound wave to travel from the center of the source region to the edge before the heat addition has occurred.

$$\tau = \frac{t_e a_0}{r_0} \quad (2)$$

In this equation, τ is the effective dimensionless time of energy addition, t_e is the effective time of energy addition in seconds, a_0 is the velocity of sound in the source region prior to the addition of energy (m/s), and r_0 is the radius of the source region.

Strehlow and co-workers have studied bursting spheres; the homogeneous ramp addition of energy with a number of characteristic time periods (this essentially models a spark); constant velocity and accelerating flames

propagating from the center of the source region; and constant velocity and accelerating flames propagating from the edge of the source region toward the center. These studies have been performed in a systematic manner for a large range of source conditions. In general, it was found that shock over-pressure and energy-scaled positive impulse in the near field are markedly affected by the nature of the source region. Additionally, it was found that if the energy density in the source region is high enough and if the characteristic time for energy addition in the source region, τ , is short enough, far-field equivalence in overpressure is obtained for these nonideal sources. It is also found that energy-scaled positive impulse is conserved irrespective of the nature of the source region at energy-scaled distances above 0.3.

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