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U.S. Industry Opportunities for Advanced Nuclear Technology Development Phase II

April 2021

Changing the World's Energy Future

James P. Burelbach, Matt Kennedy

Idaho National Laboratory

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Idaho National Laboratory
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WORLD LEADER IN NUCLEAR AND CHEMICAL PROCESS SAFETY

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Final Report
U.S. Industry Opportunities for Advanced Nuclear Technology Development Phase II

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Submitted to:

Dr. John H Jackson
GAIN Technical Interface
NSUF Industry Program Lead
Idaho National Laboratory

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16W070 83RD STREET • BURR RIDGE, ILLINOIS 60527
(877) FAUSKE1 OR (630) 323-8750 • FAX: (630) 986-5481 • E-MAIL: INFO@FAUSKE.COM

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1.0 BACKGROUND

The Statement of Work (SOW) for this activity involves three (3) Tasks.

1. Identify key reactor safety related experimental programs where the results are vulnerable to being lost. These may include, but are not limited to:

    a. Experimental programs that were performed in the distant past and potentially not well preserved,

    b. Programs that may have been proprietary, restricted/sensitive/OUO or classified reports that were not completely captured when they were released or declassified, or

    c. Results that were only reported in expert/specialist group meetings but were never formally documented in a peer reviewed report/paper.

    Under the guidance of the Light Water Reactor Data Preservation Activity Team, five (5) "experiments or experiences" will be selected from the list of the experiments/experiences developed in the initial study (Ref. 1). The project team will search for evidence related to whether experimental data could be "at risk" of loss for one or more of these studies. Given the long-term need for commercial nuclear power to help meet the world's energy requirements, particular attention will be devoted to any experimental data, or reactor experiences, that could be useful in future designs for nuclear power plants.

2. Each of the five (5) "experiments/experiences" identified in Task 1 will be down selected to three (3) programs to capture experimental information, or observations, from analyses of an accident at a commercial nuclear power plant. Each of these three (3) will then be researched to locate reports, books, reviewed technical papers, etc., to ascertain the extent of information that has been reported, but not necessarily archived. For each of the selected programs, FAI will document the number of papers found, both publicly available and proprietary, that either describe the measurement information or compare analytical approaches to the experimental measurements. This research will be documented according to the structure developed in the initial study (Ref. 1). Once this is complete, one (1) of these three (3) programs will be selected to prepare a demonstration archival document of the available information, along with the requisite explanations describing what is archived and why it was selected.

3. Using the structure developed in the initial Gateway for Accelerated Innovation in Nuclear (GAIN) activity (Ref. 1), an archival electronic document/database is to be developed for the single program selected. This example will provide a basis for similar future archival activities associated with the preservation of key experimental data.

2.0 ARCHIVAL ACTIVITY

This limited scope study aims at preserving the results of experimental programs for the safety of light water cooled and advanced reactors by locating and documenting, to the extent possible, where the experimental test information for these programs has been archived. The Light Water Reactor Data Preservation Activity Team initially identified seven (7) experimental programs, exceeding the required five (5) in the scope of work, which were determined to be "at risk" of potentially losing valuable data. The seven (7) experimental programs/subject areas identified are (descriptions of each experiment/experience are provided in Section 3.0):

1. FERMI-1 Reactor Accident
2. Fission Product Behavior During the In-Pile Severe Fuel Damage Test SFD I-4
3. Containment Iodine Computer Code Exercise Based on Radioiodine Test Facility (RTF) Experiment
4. Wide Range Piping INtegrity Demonstration (WIND) Project
5. Iodine Chemical Research in Canada
6. High Temperature Fission Product Chemistry and Transport in Steam
7. Anything related to radioactive Methyl Iodide

Capturing experimental data that could be in jeopardy of being lost because it is currently not clearly archived is the initial step in the screening criteria. For example, during the first GAIN activity (Ref. 1), it was found that some of the Marviken large-scale steam-water critical flow experiments were not included in the Organization for Economic Co-operation and Development (OECD) archival program for the large scale Marviken experiments. With permission of the GAIN Office, copies of the missing test data were offered to the OECD archival program so experimental information for all these large-scale experiments would be available for scientists and engineers in the future. (NOTE: to date, there has been no response to FAI's offer, however the response is likely affected by the working conditions imposed by individual countries to fight the COVID-19 pandemic.) Using a similar process, which was developed during the first GAIN activity, the Light Water Reactor Data Preservation Activity Team selected a list of seven (7) experiments/experiences from Appendix B of Ref. 1 which were not clearly archived and are critical for the safety basis for current and planned reactors. These seven (7) were considered wide ranging across a variety of topics and would provide the best example to frame future archival activities.

As discussed in detail in the following section, the existing material describing the Fermi 1 accident behavior and the subsequent analysis of the plant data, appeared to be in a situation where some, or all, of the data could be lost. More specifically, the American Nuclear Society (ANS) book describing the design, construction, operation, and accident is archived by ANS, but the calculations that were performed by the plant staff following the accident were reported at an international conference and the proceedings/minutes from conferences can be difficult to retrieve, if not completely lost over time. For this GAIN activity, the preservation of the calculations of the plant staff was selected because of the natural nuclear shutdown response illustrated by the results. These references were then used to illustrate how the information could be archived within a computer system (the FAI computers were used for this demonstration).

With the Fermi 1 accident serving as the primary example, the other experiments were selected (Items 2 through 7 above) as possible candidates for archiving because they differ from those used in the first GAIN archival activity and the Fermi 1 event. This was done to emphasize that there are many scientific phenomena, and experimental studies, forming the basis of reactor safety evaluations.

Once these seven (7) candidate experiments/experiences were selected, searches for possible sources (libraries, experimental databases, etc.) that may contain relevant information regarding these experiments were performed. Journal articles, national laboratory reports, university theses, and papers presented at specialist meetings were screened to find experimental data in jeopardy of being lost. From this literature review process, programs 1 through 5 of the original seven (7) shown on the previous page were identified to be most "at risk" of losing critical data for reactor safety and therefore were researched in more detail. The two programs not selected (items 6 and 7 from the above list) were not included due to a lack of relevant information during the initial literature search.

Section 3.0 provides a description of the extent of the information found, and the archival status of records associated with each of the five (5) experiments/experiences. Using the detailed information identified in Section 3.0, the beginnings of an electronic archival database are presented in Section 4.0. The archival database provides an example of how data could be presented to identify the available information and archival location. A sample set of filter and search criteria to make the database user friendly is also outlined in Section 4. Using the framework developed and knowledge gained during this project, Section 5.0 presents potential next steps. These next steps are focused on how to correlate data within an electronic database, how to archive specific references which are at risk of being lost, and how to prioritize the remaining experiments/experiences from Appendix B of Ref. 1.

3.0 ARCHIVAL EXAMPLES

As discussed in the preliminary study (Ref. 1) related to the preservation of key experimental (and nuclear power plant response to challenging conditions), candidates for archival information need to be associated with a demonstration of one or more important phenomena. Of particular interest are reports, or papers, that could be lost or accidentally discarded from library shelves. When such conditions are identified, the related information should be captured in an archival format to support its use in further scientific developments.

This section provides a detailed review of five (5) experimental programs or reactor events which were determined to be the most “at risk” of losing critical data for reactor safety basis of light water or advanced reactor concepts. The original scope of work (Section 1.0) required a detailed analysis of three (3) experimental/experiences. The preservation team was able to exceed the original scope of work and analyzed five (5) of the seven (7) identified programs determined to be most “at risk” from Section 2.0. Most “at risk” was determined using engineering judgment and discussions with the experts on the Light Water Reactor Data Preservation Activity Team based on the available data which could be located through an initial literature search. The two programs not selected (items 6 and 7 from the list in Section 2.0) were not included due to a lack of relevant information during the initial literature search. The lack of information could indicate several things:

1. The experiments/experiences are archived by an organization or in a database which the team did not have access too,
2. The experiments/experiences are considered proprietary or classified and unavailable to the team, or
3. Data for the experiments/experiences is already being lost.

These detailed examples discussed in the following sub-sections provide a framework for how the research and archival process should be carried out for future archival activities.

3.1 FERMI-I Reactor Accident

3.1.1 Background

Fermi 1 was a 150 MW(e) fast breeder reactor used for commercial electricity production first proposed to the Atomic Energy Commission (AEC) in March of 1955 as a Demonstration Program. This proposal was accepted by the AEC in August of that year. This reactor design was for an enriched metallic core with the fuel material consisting of uranium – molybdenum alloy in the form of pellets that fit within a zirconium cladding. One hundred forty (140) of these 0.158-inch diameter fuel pins were arranged in a closely packed square array to form a 12 x 12 fuel assembly. Each assembly had stainless steel support pins in each corner of the array to anchor the pins in place both axially and in the transverse direction. The uranium metal fuel was in the form of cylindrical pellets that were held within the zirconium fuel pin cladding of each pin, and liquid sodium was the coolant for this core design.

As the design and construction of this reactor neared the completion stage, concerns were raised regarding possible accident conditions that could be developed if the reactor core could be overheated, in the event of a blockage within the closely packed array of fuel assemblies. Discussions related to these concerns led to the need for a feature in the lower plenum that could capture any molten core materials that may potentially be generated if such a blockage were to be generated. To address these concerns, a set of six (6) zirconium plates were installed in the lower plenum. This late addition to the Fermi 1 design initiated the accident when one (1) of the six (6) zirconium plates, located in the inlet plenum, broke loose from its mounting and was propelled upward against the bottom of the reactor core. In addition, the bottom to the core formed a horizontal plane (flat bottom) with the liquid sodium flowing directly upward into the core from the lower plenum. As a result, the zirconium plate could be pressed against this lower surface by the upward sodium flow and cause a substantial decrease in the sodium coolant flow delivered to several fuel assemblies. With the solid fuel assemble can walls, a blockage at the inlet to a fuel assembly meant that the entire fuel assembly could be starved of coolant.

With this coolant flow starvation, the reactor fuel overheated and eventually melted within the fuel assembly. The associated increase of the nuclear fuel materials within the affected fuel assemblies caused an upward axial expansion of the fuel pins in these assemblies. This natural response produced a negative reactivity response, and the local melting and overheating of the fuel caused the future development of negative reactivity within the core. Everything else remaining the same, without any other action, this would have been sufficient to cause the reactor to shut down. However, during this testing phase, the reactor had been put on automatic power control and this automatic system had the capability of withdrawing the control rods to compensate for small negative perturbations. Consequently, as the negative reactivity formed within the core, the automatic control system countered this by withdrawing the rods required to maintain the desired core power. This is documented in the American Nuclear Society (ANS) book "Fermi-1: New Age for Nuclear Power" with the following passage beginning on page 228 (Ref. 2):

> *"At about 2:20 pm, the rise in power was begun again and continued until 8000 kW was reached where there was a brief hold to put the reactor on automatic control. This was an automatic system for taking the reactor up in power at a controlled rate and involved a somewhat complex withdrawal pattern of the two operating control rods, one designated the regulating rod and the other the shim rod. While the net motion for these rods was out or the core to increase system reactivity and, thus, increase power, for*

> *reasons of optimum control there were times when the regulating rod was actually inserted, and the shim rod withdrawn to compensate. The significant point is that with this fairly complex motion of the control rods, it was not immediately obvious precisely how much reactivity was introduced by rod withdrawal."*

While this feature of having automatic control of the reactor core power is necessary for long term operation, in the case of the Fermi 1 reactor the automatic control overwhelmed the inherent negative core responses resulting from the physical behavior of the core following the unforeseen incident of the zirconium plate breaking loose and being lifted against the bottom of the reactor core. Consequently, this set of circumstances led to the shutting down of the reactor core. With the removal of the damaged fuel assemblies, the fundamental lesson learned is that there are inherent natural core responses within metal fueled, sodium cooled, fast reactor systems that are capable of shutting down the nuclear reaction in a controlled manner. This fundamental insight must not be lost.

3.1.2 Information to be Archived

As discussed in the paper authored by Duffy and Jens (1967) (Ref. 3), the information recorded during the transient was the reactor core power as a function of time. Following the accident, this power level history was analyzed in terms of the "anomalous reactivity" that must have been introduced into the reactor core to account for the resulting reactor power given the recorded behavior of the regulating rod and the shim rod. The information from this paper is illustrated below in Figure 3-1 with the upper figure being the measured core power and the bottom graphs the "anomalous reactivity" deduced from the core power and the rod movements. These two (2) figures capture the inherent features that act to shut down the nuclear reaction if the core begins to overheat.

As discussed by Duffy and Jens (1967), the figure showing the "anomalous reactivity" was developed by considering the time histories of the shim and regulating rods to determine the reactivity that could be due to the various positions of the rods. "The reactivity needed to achieve a reactivity balance was assigned to the anomalous reactivity effects". A close examination of the lower figure shows the results of these reactivity calculations (small black dots) and these show that the anomalous reactivity was essentially zero until about 14:28 hours, at which time the reactor power was approximately 13 MWt. When the power increased above this value, the magnitude of the anomalous reactivity became apparent and displayed a negative characteristic with the magnitude increasing in a near linear manner as the core power increased. This linear rate was -0.5 cent/MWt. When the reactor power reached approximately 18 MWt, the anomalous reactivity took on a much steeper negative characteristic that was found to be more than three (3) times the initial linear rate.

Overall, these post-accident observations showed a maximum reactivity loss of 26 cents, which decreased further to 23 cents when the power was decreased prior to scramming of the reactor. This latter value was found to be in close agreement with subcritical reactivity measurements performed after the event that displayed a permanent loss of 22 cents. From this data, it was presumed that some fuel had been melted and repositioned within the core. Several of the likely questions, relevant to the safety basis, which the plant staff, technical experts, and regulatory agencies focused at that time covered several broad categories which are summarized below:

(a) Did fuel melting occur?
(b) What could have caused fuel melting?
(c) If the development of negative reactivity was due to repositioning of the reactor fuel, how was it repositioned?
(d) If fuel melting occurred, how many subassemblies were affected?
(e) Since the reactor was successfully shutdown, is there any possible fuel configuration that could overwhelm the $8.00 of negative associated with the six boron carbide safety rods (secondary criticality)?

To address these likely questions, the plant staff analyzed the possible conditions that could have developed within the core due to fuel melting. This study included three (3) different sets of analyses to determine the extent of fuel damage: (1) thermocouple analyses to assess temperature differentials across core subassemblies, (2) a reactivity loss analysis, and (3) analysis of the fission products in the cover gas and in the primary sodium coolant. It should also be noted that the six (6) boron carbide safety rods inserted into the core by the shutdown procedure had a reactivity effect of about $7.8. This negativity reactivity was found to be far greater than any configuration that could have developed as a result of melting that could occur within the reactor core.

3.1.3 How Should the Information be Archived?

The papers discussing this event, and the ANS book, need to be archived with the suggested framework being an electronic format. However, there are parts of the information that may not be transcribed in a manner that is completely recoverable. For example, the small black dots mentioned above reflect the measurements made by the staff scientists and engineers (those that had first-hand knowledge of the reactor core behavior) and these are not easily discernible in the current figure due to the image resolution quality. Consequently, it is suggested that these are features that could be lost and should receive special attention to ensure that this important information is retained. At this time, the references discussing the event are two (2) papers written by members of the technical staff, a special feature paper in the Nuclear News Magazine (a condensed version of the full technical paper presented at the International Conference on the Safety of Fast Breeder Reactors in Aix-en-Provence, France) and the ANS published book on the Fermi 1 reactor that discusses the design, construction and operation of the reactor, including the fuel melting accident. These references are (Refs. 2-5):

Alexanderson, E.P. (editor) and Wagner, H.A. (Editorial Director), 1979, FERMI-1: New Age for Nuclear Power, published by the American Nuclear Society.

Duffy, J.G. and Jens, W.H., 1967, "Investigation of the Fuel Melting Incident at the Enrico Fermi Atomic Power Plant", Paper 2-15, ANS Transactions 101.

McCarthy, W.J. and Jens, W.H., 1967, "A Review of the Fermi Reactor Fuel Damage Incident and a Preliminary Assessment of the Significance to the Design and Operation of Sodium Cooled Fast Reactors", Proceedings of the International Conference on the Safety of Fast Reactors, Aix-en-Provence, Va-1.

McCarthy, W.J. and Jens, W.H., November 1967, "Enrico Fermi Fast Breeder Reactor Fuel Damage", American Nuclear Society, Nuclear News Monthly Magazine, pp 54-57.

Perhaps the most important information that is derived from the reactivity calculations for the largest rate of increase in the magnitude of the anomalous reactivity is given in Figure 6 of the Duffy and Jens (shown below as Figure 3-3), which shows a relatively consistent average rate of increase of – 8 cents/minute with three (3) perturbations. This could be due to the movement of molten materials. There are several phenomena that could be causing this overall decrease in the core reactivity, but the major insight that is demonstrated by these results is that the natural behavior of the materials and design was acting passively to shut down the nuclear reaction.

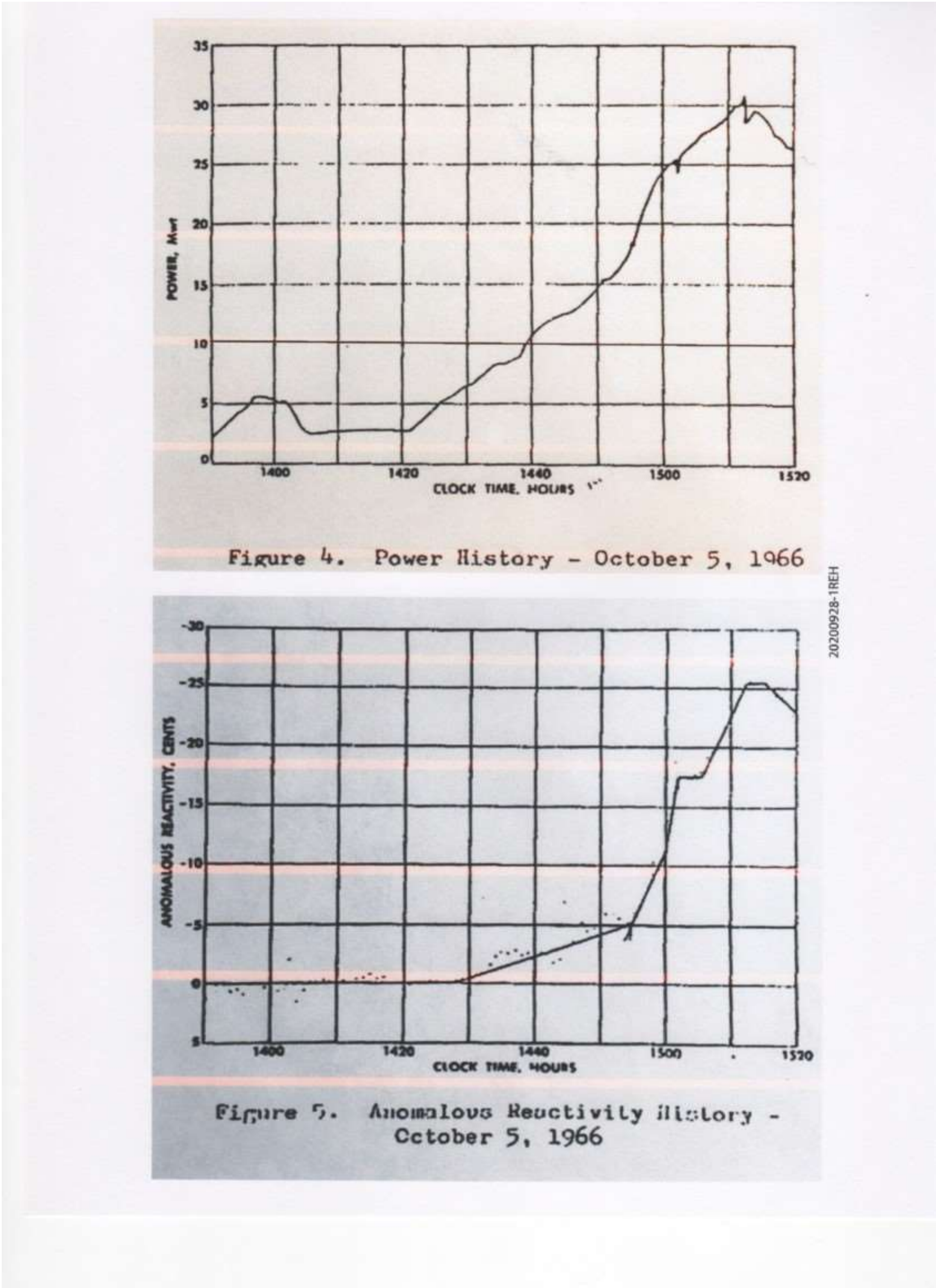


Figure 3-1 Composite illustration of the reactor power history and the calculations related to the development of anomalous reactivity in the reactor core as a result of the natural processes associated with core overheating.

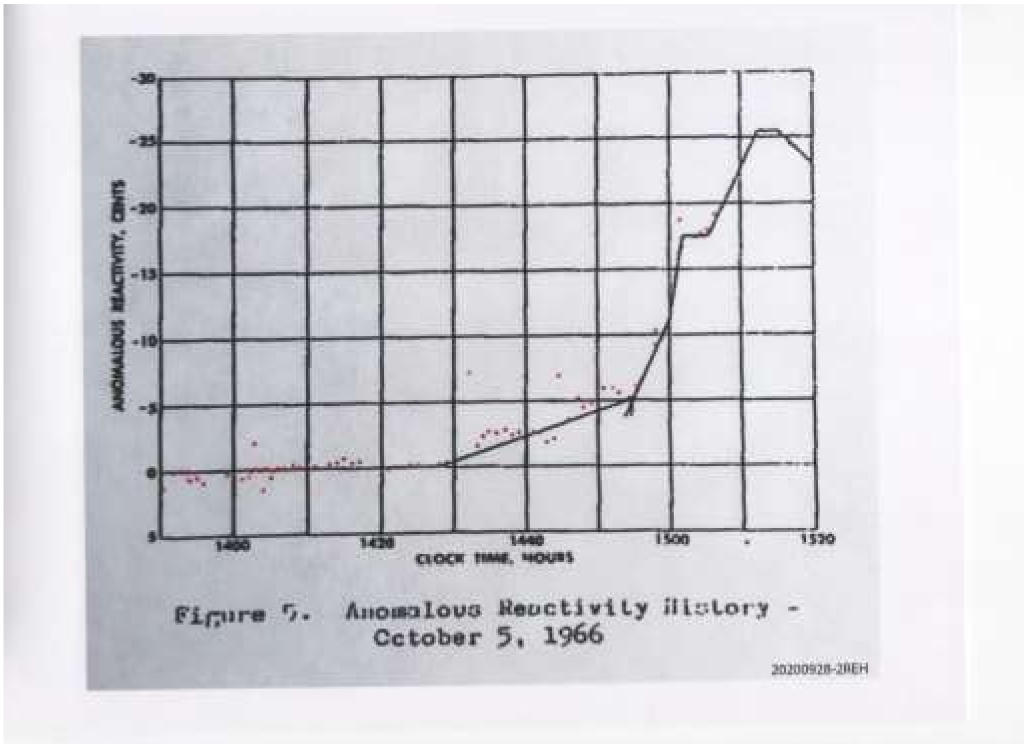


Figure 3-2 Enhanced Size of the Points Showing Calculational Results Performed by the Fermi-1 Staff

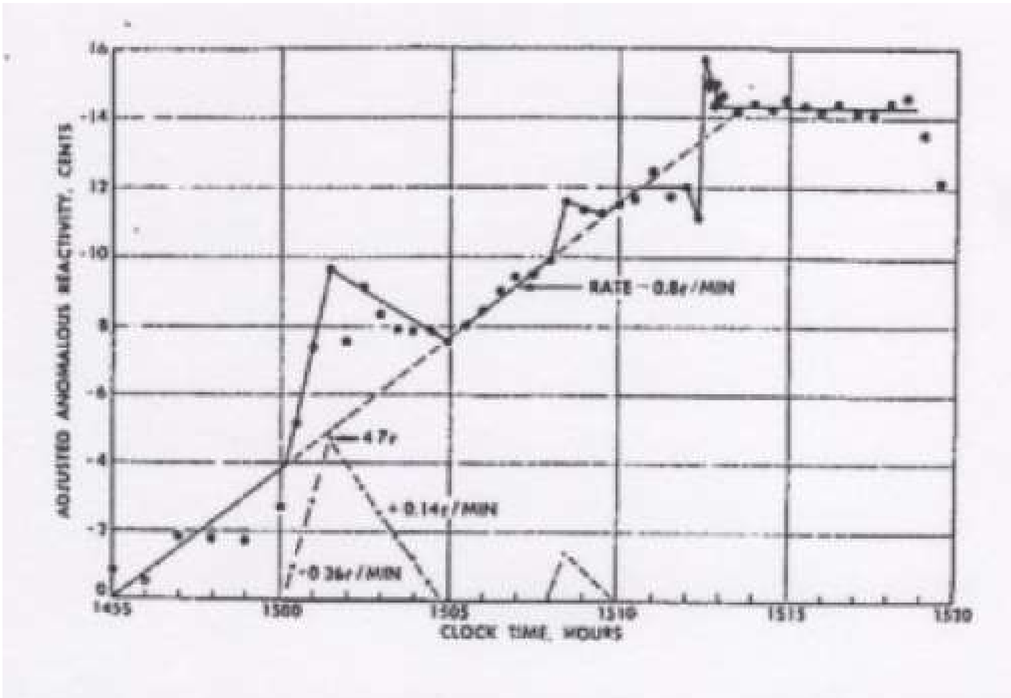


Figure 6. Adjusted Anomalous Reactivity History

Figure 3-3 The results of the calculations in the time when the formation of the negative reactivity was increasing at the largest rate.

A previous report (Ref. 1) provided a possible way in which the archival of such important information could be conducted suggested the following structure for listing the papers and reports that are available on the subject are presented in Table 3-1.

Table 3-1 Archival Comprehensiveness Alpha Numeric Categories

Alpha Numeric Category	Description of Reference Source Category
A	The original experimental data records or test reports that include tables or graphs (unprocessed or processed) of the measured information for a given experiment.
B	The experimental test report(s) that includes the processed data for those measurements judged to be the most important but does not satisfy the criterion in "A".
C	A program summary report that provides an overview of the test results.
D	Peer reviewed papers for technical journals that have been published in the open literature by personnel directly associated with the experimental program.
E	Peer reviewed papers for technical journals that have been published in the open literature by analysts that are using the experimental data.
F	Industry reports that have been reviewed by a government agency as part of a licensing application.
G	Technical papers that have not received peer reviews but were presented at group or specialist meetings.
H	Slides used for a presentation of experimental results at a group or specialist meeting.

Considering the above categories, the information that is provided in the paper by Duffy and Jens (Ref. 3), the most appropriate level is "G", since there is no record of a peer review process. However, it should be noted that the figure showing the level of the "anomalous reactivity" does include the results of the individual calculations performed by the Fermi 1 technical staff, which are the individuals with a working knowledge of the reactor design and operation.

3.2 Fission Product Behavior During the In-pile Severe Fuel Damage Test SFD 1-4

3.2.1 Background

The Severe Fuel Damage (SFD) series of tests were performed at the Power Burst Facility (PBF) to obtain the data necessary to understand fuel behavior, fission product release, transport and deposition, and hydrogen generation during severe accidents.

Test SFD 1-4 was the fourth large scale, in-pile test of the SFD Research Program. The objective of the SFD 1-4 test was to reproduce conditions of temperature, fuel damage, fission product release, hydrogen generation, and control rod material behavior that are representative of an unmitigated, severe, light-water reactor accident caused by the loss of coolant through a small break in the primary coolant piping.

The SFD 1-4 test bundle included twenty-eight (28) PWR type fuel rods 1m in length and 4 stainless-steel-clad Ag-In-Cd control rods in Zircaloy guide tubes. The experiment procedure was developed to simulate the fuel conditions following a loss of coolant through a small break in the primary coolant piping. Twenty-six (26) of the twenty-eight (28) fuel rods were previously irradiated to a burnup of about 36,000 MWd/tU. The bundle nuclear power was used to simulate the decay heat representative of a commercial reactor following a scram. First, the inlet flow to the bundle was reduced while decreasing the bundle nuclear power to simulate the decay heat. This caused dryout, which started the Zircaloy oxidation process. Then, the bundle power was increased causing the temperature to increase to values exceeding 2400 K, approaching fuel melting. The high temperatures resulted in the Zircaloy melting, fuel liquefaction, control rod rupture and melting, material relocation and fission product release. After the 224-s power hold, the reactor power was slowly decreased and eventually the reactor was shut down.

After the test, the effluent line was pressurized with nitrogen and kept above saturation temperature until the deposition rod was removed from the effluent outlet line. The fuel bundle and the effluent line were then flushed with water to study the effects of flushing on fission product and aerosol deposition.

3.2.2 Information to be Archived

The final report of the testing campaign with the results of the experiment was published as (Ref. 6):

> Petti, D A, Martinson, Z R, Hobbins, R R, Allison, C M, Carlson, E R, Hagrman, D L, Cheng, T C, Hartwell, J K, Vinjamuri, K, and Seifken, L J. Power Burst Facility (PBF) severe fuel damage test 1-4 test results report. United States: N. p., 1989. Web. doi:10.2172/5983389.

This paper has already been archived and is retrievable on the website for the Office of Scientific and Technical Information (OSTI) website at the following address:

https://www.osti.gov/biblio/5983389-power-burst-facility-pbf-severe-fuel-damage-test-test-results-report

The following paper presents some of the preliminary results of the experiment. Many of these results are presented in the final report published by Petti et. al (shown above). However, for continuity the preliminary results (Ref. 7) should also be captured within an electronic database.

> K. Vinjarnuri, D. Osetek, D. Petti, D. H. Meikrantz, "Fission product behavior during the in-pile Severe fuel damage test SFD 1-4", Second American Chemical Society Symposium on Nuclear Reactor Severe Accident chemistry, Toronto, June 5-10, 1988

The following provides a listing of the results from Vinjarnuri (Ref. 7), which were included in the final experimental report (Ref. 6).

- The deposition concentration (Figure 4 of Ref. 7) is reported in Figure 103-Figure 114 in Ref. 6.
- The fractional release rates (Figure 3 in Ref. 7) is reported in Figure 91 of Ref. 2.
- The fraction of fission products (pre-flush and post-flush, Table 1 and Table 2 of Ref. 7) are reported in Table 21 and Table G-5 through Table G-12. However, there is a slight discrepancy between the results reported in Ref. 6 to those reported in Ref. 7, which can be due to the preliminary nature of the results of Ref. 6.

3.3 Containment Iodine Computer Code Exercise Based on a Radioiodine Test Facility (RTF) Experiment

3.3.1 Background

The International Standard Problem (ISP) exercises are comparative exercises in which predictions of different computer codes for a given physical problem are compared with each other or with the results of a carefully controlled experimental study. The ISP No. 41 exercise was developed at the recommendation at the Fourth Iodine Chemistry workshop held at the Paul Scherrer Institute (PSI), Switzerland in June 1996:

> *"…the performance of an International Standard Problem as the basis of an in-depth comparison of the models as well as contributing to the database for validation of iodine codes."*

The criteria for the selection of the Radioiodine Test Facility (RTF) test as a basis for the ISP-41 exercise were:

1. Complementary to other RTF tests available through the Phebus and Advanced Containment Experiments (ACE) programs,
2. Simplicity for ease of modeling, and
3. Good quality data.

An RTF experiment with a well-defined configuration and testing sequence performed under controlled, and very limited, conditions was chosen as a starting point for evaluation of the various iodine behavior codes. The RTF test was conducted in a stainless-steel vessel at 25℃ and at a dose rate of 1.4 $kGy \cdot h^{-1}$. The test, which started with about 1×10^{-5} $mol \cdot dm^{-3}$ CsI in the aqueous phase, was conducted in two (2) stages. In both stages, the initial pH was 10, followed by multiple, and controlled, stepwise decreases in pH (to 7.2 in Stage 1 and to 5.5 in Stage 2). At the end of Stage 1, the initial charge solution was discarded, the vessel was rinsed repeatedly to remove adsorbed iodine and a fresh solution of CsI was added to commence Stage 2. The sequence of events of Stage 1 and 2 is presented in Table 3-2 and Table 3-3, respectively.

Table 3-2 Experimental events - Stage 1

Time (h)	Event
0	Tracer Added - pH 10
23.6	pH control set to 9
96.5	pH control set to 8.5
164.7	Unscheduled pH excursion to 7.8
166.7	pH control set to 8.5
181.7	Unscheduled pH excursion to 7.8
190.7	pH control set to 8.5
195.5	pH control set to 8.2
264	pH control set to 7.9
312	pH control set to 7.6
339	pH control set to 7.4
363.4	Charge Dumped - Vessel Washed

Table 3-3 Experimental events - Stage 2

Time (h)	Event
0	Tracer Added - pH 10
23	pH control set to 8.5
45	pH control set to 7.9
118	pH control set to 6.5
168	pH control set to 5.5
192	pH control set to 10
285	Charge dumped, Vessel Washed

3.3.2 Information to be Archived

The results of the experiment that were recorded, and need to be archived, are the observed gas phase and aqueous phase iodine concentrations.

This report is currently archived by the Nuclear Energy Agency of the OECD as follows (Ref. 8):

> International standard problem (ISP) No 41 Containment iodine computer code exercise based on a radioiodine test facility (RTF) experiment (NEA-CSNI-R--2000-6-VOL-1). Nuclear Energy Agency of the OECD (NEA)

The key information to be archived is the total concentration of iodine in Stage 1 (Figure 3-4) and Stage 2 (Figure 3-5), and the calculated and measured iodine distribution at test end (Table 3-4 and Table 3-5).

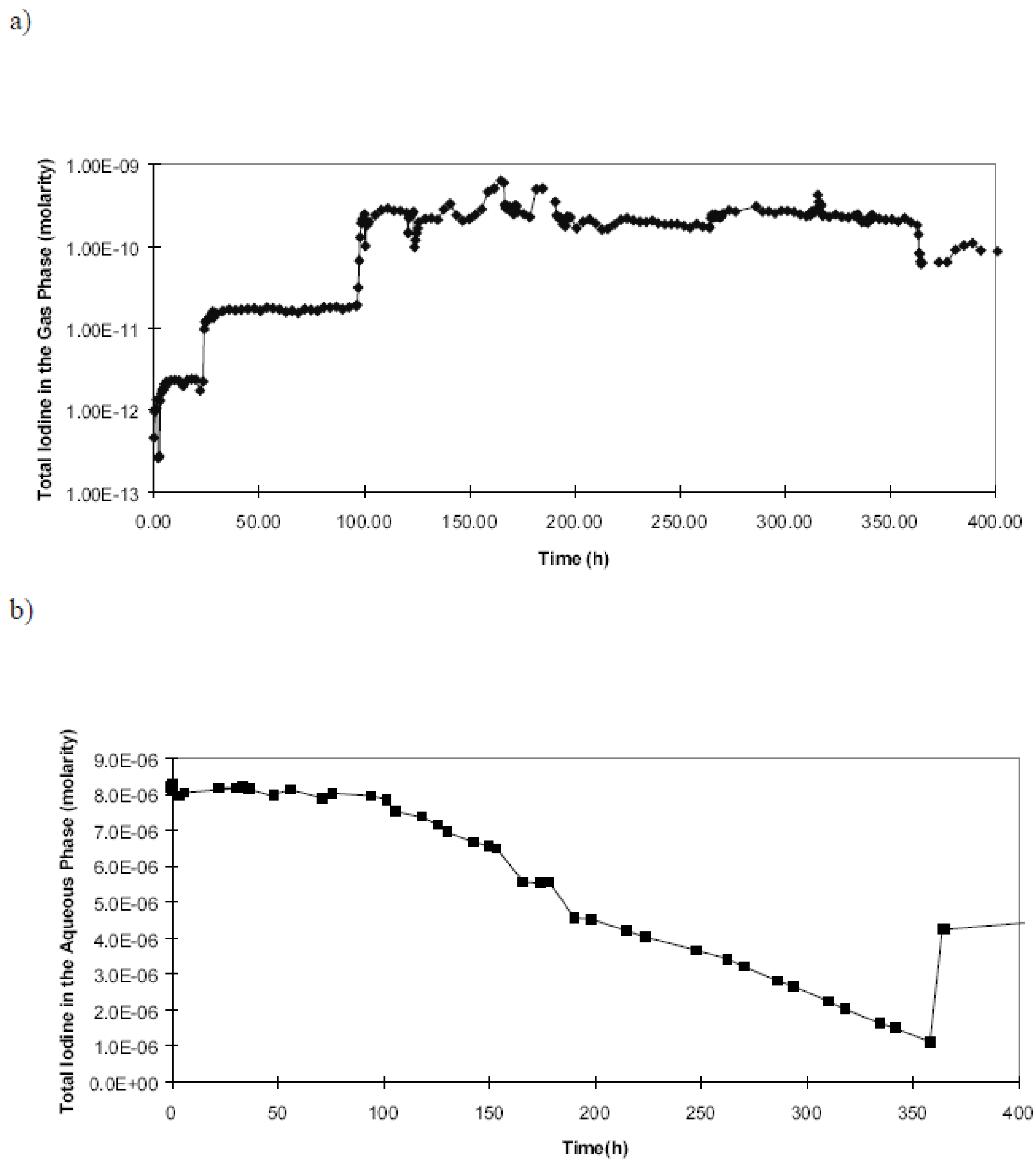
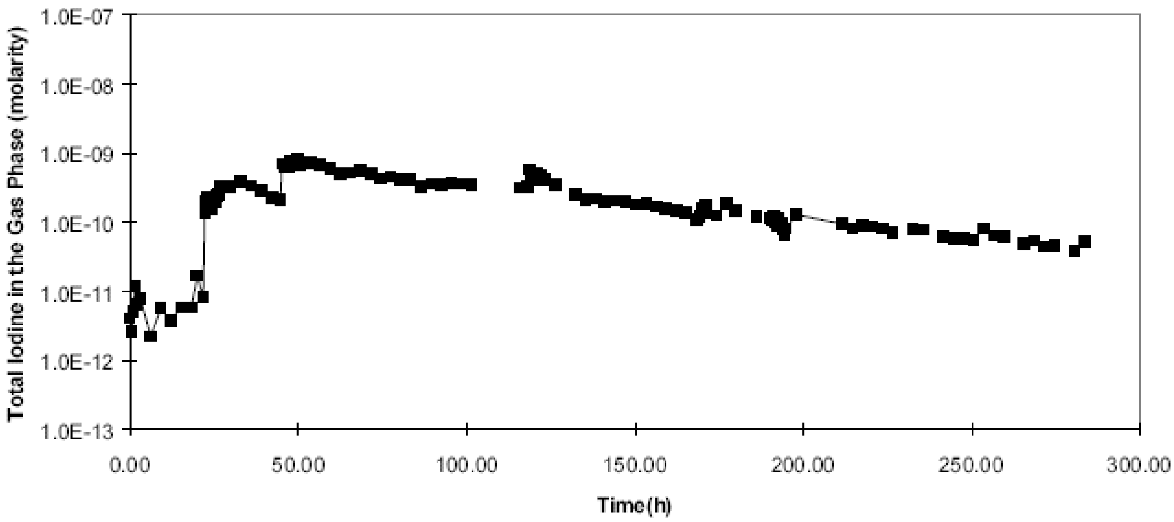


Figure 3-4 Measured Total Concentrations of Iodine in Stage 1: (a) Gas Phase and (b) Aqueous Phase

(a)



(b)

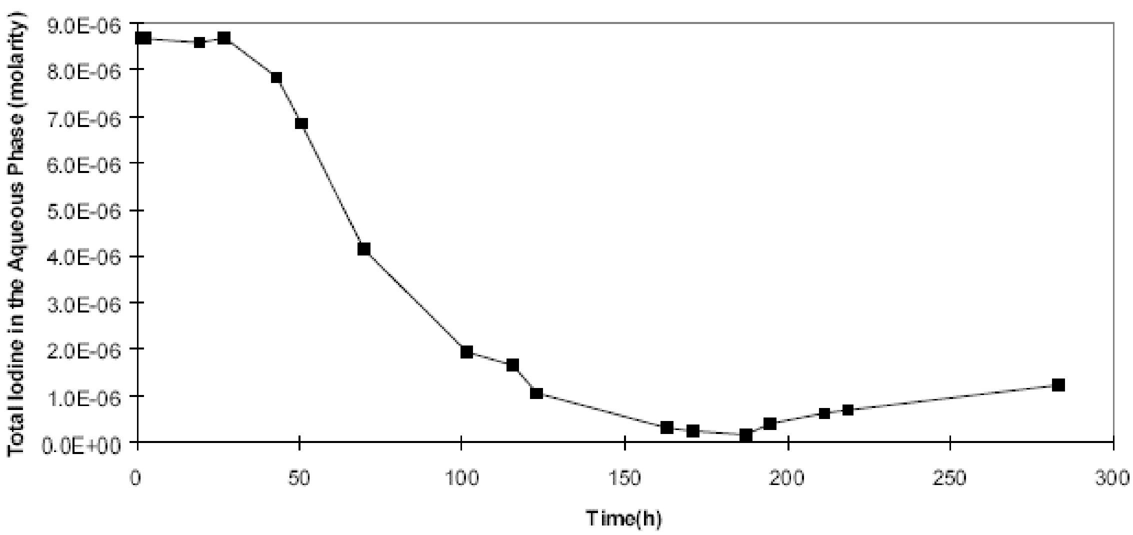


Figure 3-5 Measured Total Concentrations of Iodine in Stage 2: (a) Gas Phase, and (b) Aqueous Phase

Table 3-4 Calculated Vs. Experimental Iodine Distribution at Test-end 1st Calculation

	Stage 1 Percentage Iodine Inventory at Test End[a]				Stage 2 Percentage Iodine Inventory at Test End			
	Gas	Aq.	Gas walls	Aq. walls	Gas	Aq.	Gas walls	Aq. walls
CIEMAT[b] (Case 1)	.006	93.3	6.7	-	.006	85.9	14	-
CIEMAT[b] (Case 2)	.004	91.7	5.0	3.32	.005	81.4	10.1	
CIEMAT[b] (Case 3)	.03	55.7	44	-	.012	43.7	56.3	-
CIEMAT[b] (Case 4)	.019	44.4	33.2	22.2	.008	32.8	36	30.9
IPSN	.03	91	8.7	-	.02	88	12	-
NRIR	.04	10	89	-	.01	20.6	79	-
Siemens	.6	99.4	1.5×10^{-5}	-	2.6×10^{-4}	100	1.1×10^{-4}	-
GRS	.34	99.7	3.5×10^{-4}	-	2.6×10^{-4}		1.8×10^{-4}	-
PSI	.4	99.6	3.5×10^{-6}	-	3.5	96.4	9.5×10^{-5}	-
JAERI	.14	40.6	59.3	-	.08	88.3	11.7	-
Sandia	.007	24	76	-	.002	25.5	74.5	-
AECL	0.03	10.8	89.7		.003	16.4	83.6	
Experiment	**.02**	**12.4**	**87.6**	-	**.007**	**13.6**	**86.4**	-

[a] Test end defined to be at 363 h, when the contents of the sump were drained.
[b] Case 1: $k_{13} = 1.7 \times 10^{-3}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.5 no aqueous phase adsorption
Case 2: $k_{13} = 1.7 \times 10^{-3}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.5 aqueous phase adsorption
Case 3: $k_{13} = 2.5 \times 10^{-4}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.25 no aqueous phase adsorption
Case 4: $k_{13} = 2.5 \times 10^{-4}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.25 aqueous phase adsorption

Table 3-5 Calculated Vs. Experimental Iodine Distribution at Test-end: 2nd Calculation

	Stage 1 Percentage Iodine Inventory at Test End[a]			Stage 2 Percentage Iodine Inventory at Test End		
	Gas	Aq.	Gas walls	Gas	Aq.	Gas walls
CIEMAT[b] (Case 1)	1.1×10^{-4}	87.8	12.2	2.3×10^{-4}	75.4	24.6
CIEMAT[b] (Case 2)	4.9×10^{-4}	20.6	79.4	4.3×10^{-4}	30.2	69.8
CIEMAT[b] (Case 3)	4.9×10^{-4}	1.1	98.9	7.5×10^{-4}	22.9	77.1
CIEMAT[b] (Case 4)	4.9×10^{-4}	13.7	86.3	5.1×10^{-4}	34.7	65.3
CIEMAT[b] (Case 5)	1.8×10^{-4}	76.6	23.4	2.8×10^{-4}	85	15
IPSN	2.1×10^{-4}	88.9	11.1	0.002	93.5	6.5
NRIR	0.017	6.7	93.3	0.007	13	87
Siemens	8.6×10^{-3}	70	30	0.010	51.1	48.9
GRS	1.6×10^{-3}	76	24	3.1×10^{-3}	50.7	49.3
PSI	2.0×10^{-6}	100	0	2.9×10^{-6}	100	0
JAERI	0.020	41.6	58.4	0.016	60.4	39.6
Sandia	.007	24	76	.002	25.5	74.5
AECL	0.024	10.0	89.9	.004	12.5	87.5
Experiment	**.02**	**12.4**	**87.6**	**.007**	**13.6**	**86.4**

[a] Test end defined to be at 363 h, when the contents of the sump were drained.
[b] Case 1: $k_{13} = 1.7 \times 10^{-3}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.5 no aqueous phase adsorption
Case 2: $k_{13} = 2.5 \times 10^{-4}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.25 no aqueous phase adsorption
Case 3: $k_{13} = 2.17 \times 10^{-4}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.1 no aqueous phase adsorption
Case 4: $k_{13} = 2.17 \times 10^{-5}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.1 no aqueous phase adsorption
Case 5: $k_{13} = 2.17 \times 10^{-5}$ Gy^{-1}, $k_{-13} = 2 \times 10^{-5}$ s^{-1}, n=0.1 no aqueous phase adsorption

3.4 Wide Range Piping INtegrity Demonstration (WIND) Project

3.4.1 Background

The Wide range piping INtegrity Demonstration (WIND) Project analyzes the interaction between Cesium Iodide (CsI) and Type 316 Stainless Steel and was performed at the Japan Atomic Energy Research Institute. During a severe accident of a light water reactor, fission products are released into the Reactor Coolant System (RCS), and as a result some of the fission products are deposited on the RCS piping. The fission products may interact with the piping material ultimately influencing the source term of a severe accident.

Similar studies analyzing the fission product reactions with structural materials were performed under atmospheric conditions of steam and hydrogen. However, it is possible that air ingression into the RCS occurs during a severe accident and may affect the fission product behavior. The WIND project investigated the interaction between Cesium Iodide and structural material in the air ingression condition.

A 316 Stainless Steel sample test coupon was sectioned for chemical analysis at both a constant temperature and temperature gradient. Ion chromatography (IC), scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDX), and X-ray photoelectron spectroscopy (XPS) were used to: (a) quantify the cesium and iodine deposited mass, (b) observe the morphology of deposits, (c) specify the existent elements and (d) identify the chemical form, respectively.

The previous studies concluded that Cesium Iodide will exhibit simple vapor condensation on the piping surfaces and the effect on the source materials could not be determined. The WIND project concluded that the CsI decomposed under the air ingression condition unlike the H_2 injection condition, which indicated that the CsI was less stable in the air atmosphere. In addition, the amount of CsI decomposed on the 316 Stainless Steel during the air ingression condition was very small, concluding that the chemical interaction of CsI and type 316 Stainless Steel hardly influences the source term evaluation. The EDX results showed that at a high temperature the retained mass of cesium was larger than that of iodine in the structural surface; however, the cesium compounds were not confirmed by XPS analysis. In all test conditions, it was shown through XPS analysis that iodine migrated to a maximum depth of 100 nm of the Stainless Steel surface layer. In the test with air ingress condition, EDX measurements showed that the retained mass of cesium was larger than that of iodine in the structural surface at a high temperature. The WIND project concluded that the amount of cesium and iodine retained in the 316 Stainless Steel surface was too small to influence the source term evaluation.

3.4.2 Information to be Archived

The WIND project results are discussed in a Japan Atomic Energy Research Institute Conference paper (Ref. 9):

> Hashimoto, Kazuichiro (ed.); Japan Atomic Energy Research Inst., Tokyo (Japan); 377 p; Nov 2000; p. 216-221; SARJ-99: workshop on severe accident research, Japan; Tokyo (Japan); 8-10 Nov 1999.

This paper is archived on the International Atomic Energy Agency (IAEA) website and can be retrieved at this address:

https://inis.iaea.org/collection/NCLCollectionStore/_Public/32/026/32026139.pdf?r=1

Previous experiments that did not incorporate air ingression were documented in the following reports (Refs. 10, 11):

> R. M. Elrick, et al., "Reaction Between Some Cesium-Iodine Compounds and the Reactor Materials 304 Stainless Steel, Inconel 600 and Silver, Volume II Cesium Iodide Reactions," NUREG/CR-3197/2 of 3, SAND83-0395, Sandia National Laboratories, Albuquerque, New Mexico, June 1984.

> B. R. Bowsher, "Fission-Product Chemistry and Aerosol Behaviour in the Primary Circuit of a Pressurized Water Reactor under Severe Accident Conditions," Progress in Nuclear Energy, Vol. 20, No. 3, pp. 199-233, 1987.

The first, NUREG/CR-3197/2 of 3, was documented, but not retrievable, on the IAEA website at this address:

https://inis.iaea.org/search/search.aspx?orig_q=RN:18052262

The second, Progress in Nuclear Energy Vol. 20, was retrievable on Science Direct website at this address:

https://www.sciencedirect.com/science/article/abs/pii/0149197087900060

3.5 Iodine Chemistry Research in Canada

3.5.1 Background

Periodic reviews of the state of understanding of iodine chemistry under severe accident conditions are performed by the Atomic Energy of Canada. After significant increases in the understanding of iodine interactions were accomplished in the late 1980s, and the fact that differences in reactor designs may result in a wide range of iodine behavior impacts, a study was performed to highlight which aspects were considered to be well known and which could require further research and/or experimentation.

The present understanding of iodine chemistry was discussed for three (3) main conditions: iodine behavior in the aqueous phase, in the gaseous phase, and iodine interactions with surfaces. The research concluded that iodine behavior in the gaseous phase is adequately understood, including most areas relying on thermodynamic data and the details of thermal oxidation of iodide to iodine.

It was identified that iodine behavior in the aqueous phase and interactions with surfaces needed further investigation. It was concluded that controlling the decomposition of organic species in the aqueous phase has an important impact on the aqueous iodine chemistry and that the capability for modeling these processes remained incomplete. In addition, the influence of some metal ions on iodine chemistry (specifically the catalytic reactions with H_2O_2 and O_2) remains uncertain. For the aqueous phase it was also determined that further research was required to address the uncertainties on the effects of different flow or mixing regimes in large volumes, and on differing surface to volume ratios. Predictions of the mass transfer rate may be less reliable and/or straightforward for various geometries and larger vessels.

Considering that the surfaces may be large iodine sinks, as well as sources for organic iodides, further research on the effects of iodine interactions with surfaces was suggested. Surfaces have large potential to be iodine sinks, and the existing models for iodine absorption still need- to be validated.

3.5.2 Information to be archived

The Canadian iodine chemistry research conclusions are discussed in the following report (Ref. 12):

> Weaver, K.R., W.C.H. Kupferschmidt, J.C. Wren, J.M. Ball, "The Present Status Of Iodine Chemistry Research In Canada And Its Application To Reactor Safety Analysis"

This paper is retrievable on the IAEA website at this address:

https://inis.iaea.org/collection/NCLCollectionStore/_Public/28/036/28036807.pdf

The following reports discussing the effects of iodine chemistry on surfaces could not be retrieved and may be considered for archival if they can be retrieved in the future (Refs. 15-24):

Rosenberg H.S., Genco J.M., Morrison D.L., "Fission Product Deposition and its Enhancement Under Reactor Accident Conditions: Deposition on Containment System Surfaces", Battelle Memorial Institute Report, BMI-1865, Columbus, 1969.

Genco J.M., Berry W.E., Rosenberg H.S., Morrison D.L., "Fission Product Deposition and its Enhancement Under Reactor Accident Conditions: Deposition on Primary System Surfaces", Battelle Memorial Institute Report BMI-1863, Columbus, 1969.

Rosenberg H.S., Cremeans G.E., Genco J.M., Berry D.A., Morrison D.L., "Fission Product Deposition and its Enhancement Under Reactor Accident Conditions: Development of Reactive Coatings", Battelle Memorial Institute Report, BMI-1874, Columbus, 1969.

The following reports utilized in the iodine chemistry review were all retrievable from various locations.

Lemire R.J., Paquette J, Torgerson D.F., Fletcher D.W., "Assessment of Iodine Behaviour in Reactor Containment Buildings from a Chemical Perspective", Atomic Energy of Canada Report AECL-6812, 1981.

Wren D.J., Paquette J., Wren J.C., Clough P.N., Starkie H.C., "A Review of Iodine Chemistry Under Severe Accident Conditions", Atomic Energy of Canada Report AECL-9089,1983.

Wren J.C., Ball J.M., Glowa G.A., Sanipelli G.G., "The Interaction of Iodine with Organic Material in Containment", in Proceedings of the Fourth CSNI Workshop on the Chemistry of Iodine in Reactor Safety, Wurenlingen, Switzerland, 1996.

Wren J.C., Glowa G.A., Ball J.M., "Modelling Iodine Behaviour Using URIC 3.0", in Proceedings of the Fourth CSNI Workshop on the Chemistry of Iodine in Reactor Safety, Wurenlingen, Switzerland, 1996.

Fluke R.J., Edward J.B., Weaver K.R., Evans G.J., "Advanced Containment Experiments (ACE): Evaluation of Pre-Test Code Calculations of Iodine Behaviour in the Radioiodine Test Facility", in Proceedings of the Third CSNI Workshop on Iodine Behaviour in Reactor Safety", Tokai-mura, Japan, 1992.

Postma A.K., Zavadoski R.W., "Review of Organic Iodide Formation Under Reactor Accident Conditions in Water-Cooled Reactors", Atomic Energy Commission Report, WASH-1233,1972.

Sagert N.H., "Radiolysis of Iodine of Moist Air: A Computer Study", in Proceedings of the Second CSNI Workshop on Iodine Chemistry in Reactor Safety, Atomic Energy of Canada Report, AECL-9923,1989.

Hemphill R.T., Pelletier C.A., "Surface Effects in the Transport of Airborne Radioiodine at light Water Nuclear Power Plants", EPRI-NP-876,1978.

4.0 SAMPLE ELECTRONIC DATABASE

Many of the experimental programs documented in Section 3.0 identified data which needs to be, or may already be, archived. As mentioned in the previous section, an electronic database provides the best method to organize and categorize the data related to each experimental program for future reference and retrieval if not already archived elsewhere. This section provides an overview of an example of an electronic database which captures the references for the experimental programs discussed in Section 3.0.

The example database is a stand-alone executable, written in Xaml and VB, which reads in a standard Microsoft Excel file, that contains all the pertinent information for categorizing and retrieving the necessary information. The name of the program is Nuclear Archival Electronic Database (NAED).

Figure 4-1 provides a screenshot of the initial window, which opens after launching the program executable. Within the main window, there are two (2) sub-windows which allow user interaction with the database and the referenced information. The two sub-windows can be identified by the tabs/headers as: 1. "Items Filter" and 2. "Data". The first window (left side of Figure 4-1 header "Items Filter") provides a set of filter criteria for the user to navigate the database. The second window (right side of Figure 4-1 header/tab "Data") provides the reference data in the archival database. Upon program initiation, all the data in the database is provided and can be reduced by selecting specific filter categories of interest to the user.

The filter window ("Items Filter" on the left side of the program) was set up with three (3) categories which the user can interact with to filter the data to specific experiments/experiences of interest.

- The first filter category provides a high-level categorization of the reference data.
- The second filter category provides a list of the specific phenomena studied during the experimental program or occurred during the specific accident scenarios.
- The third filter category provides a list of the reference classification based on the source/quality of data as an alphanumeric list A through H which was presented in Ref. 1 and provided in Table 3-1.

The items currently included in the filter categories include all of the experimental programs, phenomena, and experiences that were identified as part of the international survey conducted during the initial GAIN archival activity project and documented in Appendix B of Ref. 1. Many of these filter categories currently contain no associated reference data and are placeholders within the database to be populated as part of future archival activities. Figure 4-2 also shows a fourth filtering feature, below the filter category lists, along the user to perform a keyword search through a text entry field. The user can use this to search for keywords within the database should they not know exactly which filter category to select to find the data of interest. Once the user narrows down the search, the filter categories can be hidden as shown in Figure 4-3. This allows more of the tab “Data”, which contains the reference data of interest, to be shown with the program minimizing the amount of horizontal scrolling required to view the entire reference data set.

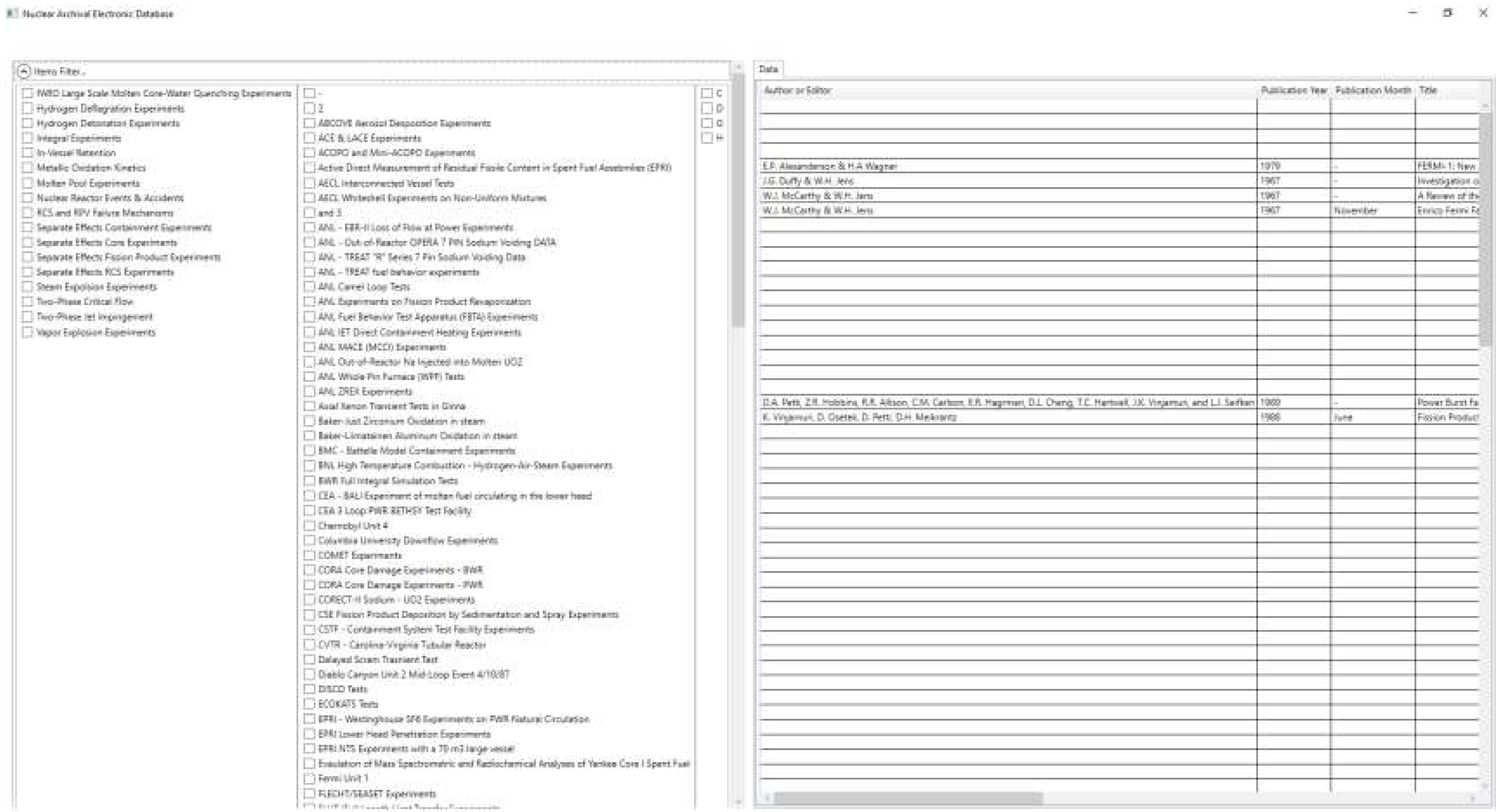


Figure 4-1 Sample Electronic Database (Initial Screen)

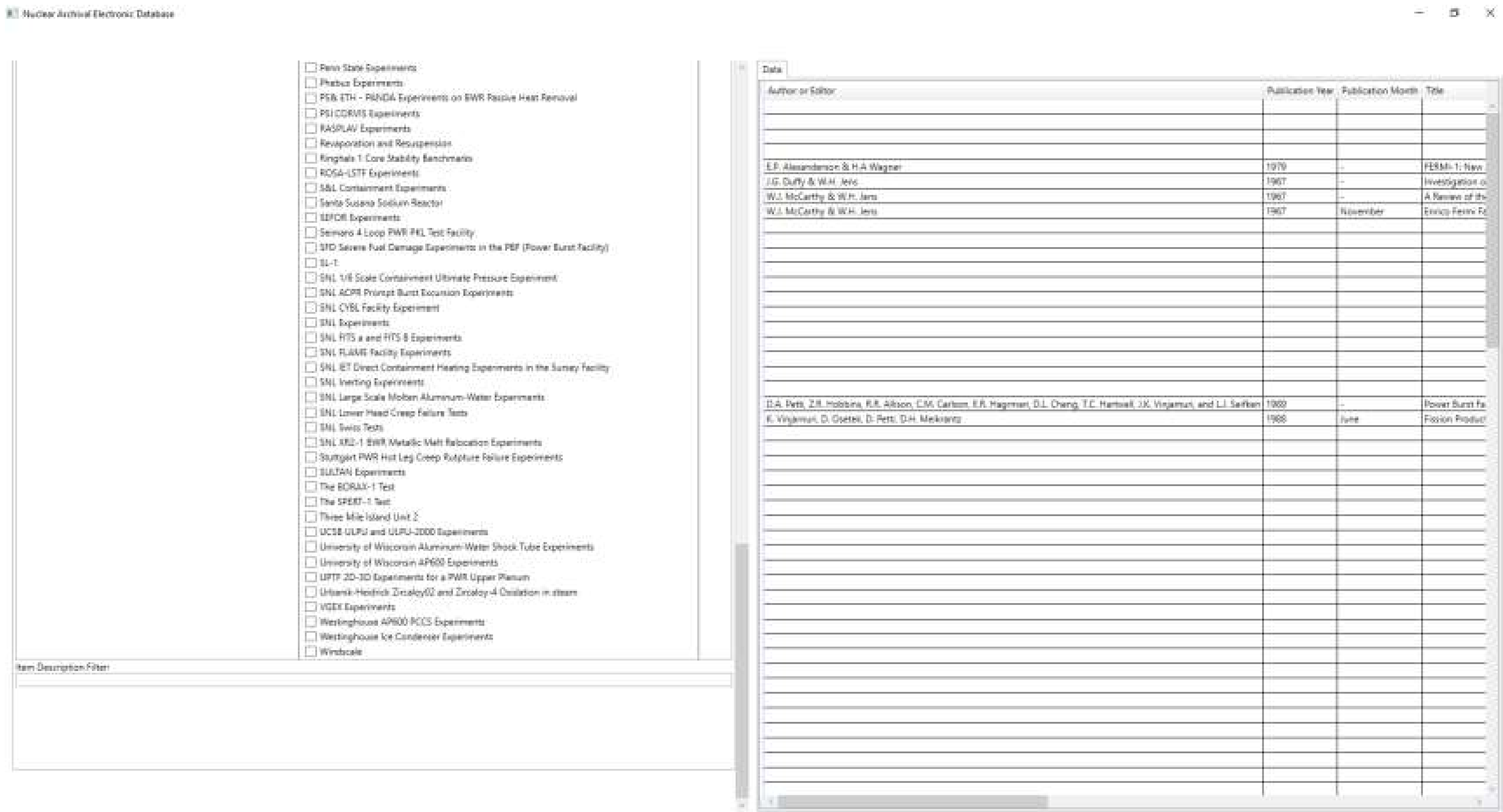


Figure 4-2 User Keyword Search Function

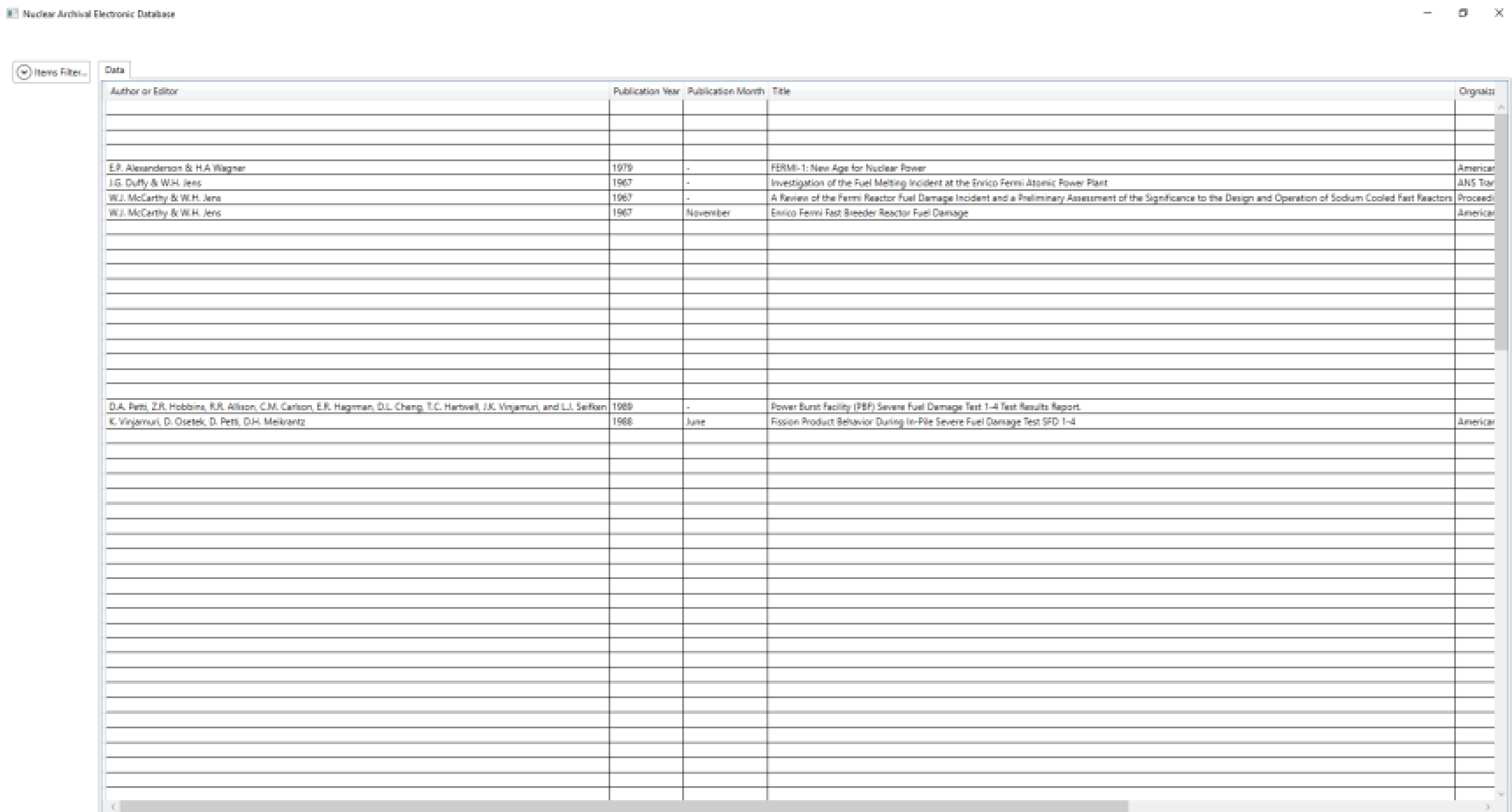


Figure 4-3 Collapsed Filtering Window

The second window in the main program, tab “Data” on the right-side of the main window, contains the specific references and the archival location. Note that the example database, shown in Figure 4-3, contains many blank rows for the experimental programs which were not included in the current work scope. These represent future experiments/experiences which need to be researched and included in the database. The “Data” window contains seven (7) columns to organize the data for each specific reference (not all columns are shown in the figures). Each reference is included as a row in the database. The columns which are focused on organizing reference data into similar information groupings is currently as follows:

1. Author/Editor
2. Publication Year
3. Publication Month (if known)
4. Title
5. Organization or Journal
6. Archived (Yes or No)
7. Archived Location

The first 5 data columns are standard reference/bibliographic data. This allows the user to identify the author, year of publication or presentation, reference title and organization which published the data. The last 2 data columns provide an assessment, by the Light Water Reactor Data Preservation Activity Team, as to whether the reference has already been archived and is retrievable by the user from the specified archive location. If a reference is already considered archived the user can use the database to save time by having all available references for a phenomena, experiment, or experience in a single database. If a reference is not already archived, Section 5.0 outlines a potential next step to capture these references before they are lost.

Figure 4-4 and Figure 4-5 provide an example of how a user could potentially use the tool to locate references for the Fermi 1 Reactor Accident. First, Figure 4-4 shows the filter categories “Nuclear Reactor Events & Accidents” in the first high-level filter category and “Fermi Unit 1” in the second detailed filter category. These are selected in the figure to show the user interaction using the filter categories. In the data window, the number of data rows is reduced to the four references which pertain to Fermi Unit 1, which are the same references discussed in Section 3.1. Figure 4-5 provides an even further reduction of the data when the third filter category representing the data quality is selected to the letter “C”. This further reduces the data down to the single reference which was determined to be from a source consistent with the data quality for category C. The data quality categories were laid out in Ref. 1 and are presented in Table 3-1.

This example for how a user would select the data applicable to the Fermi 1 accident shows how the filters help narrow down the database to the relevant information pertaining to the accident. The user can then use the horizontal scroll bar in the data window to find all the necessary information on the references. A user interested in this data would see that there is a book about the accident which can be obtained from ANS along with three (3) other papers which were identified in Section 3.0. A user would see that the two (2) papers are not currently archived and may have a difficult time tracking them down.

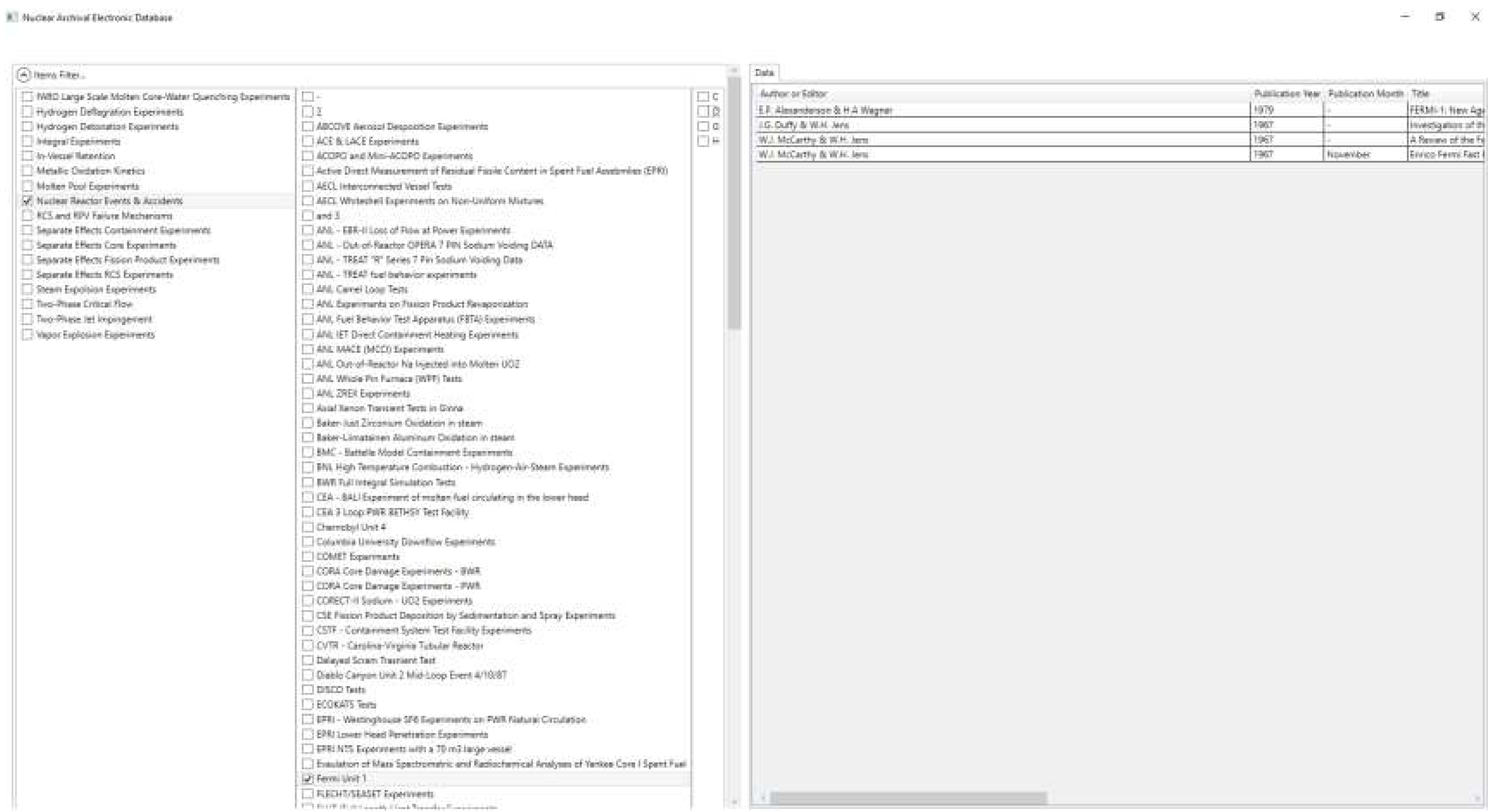


Figure 4-4 Example of Search for References Related to the Accident at FERMI Unit 1

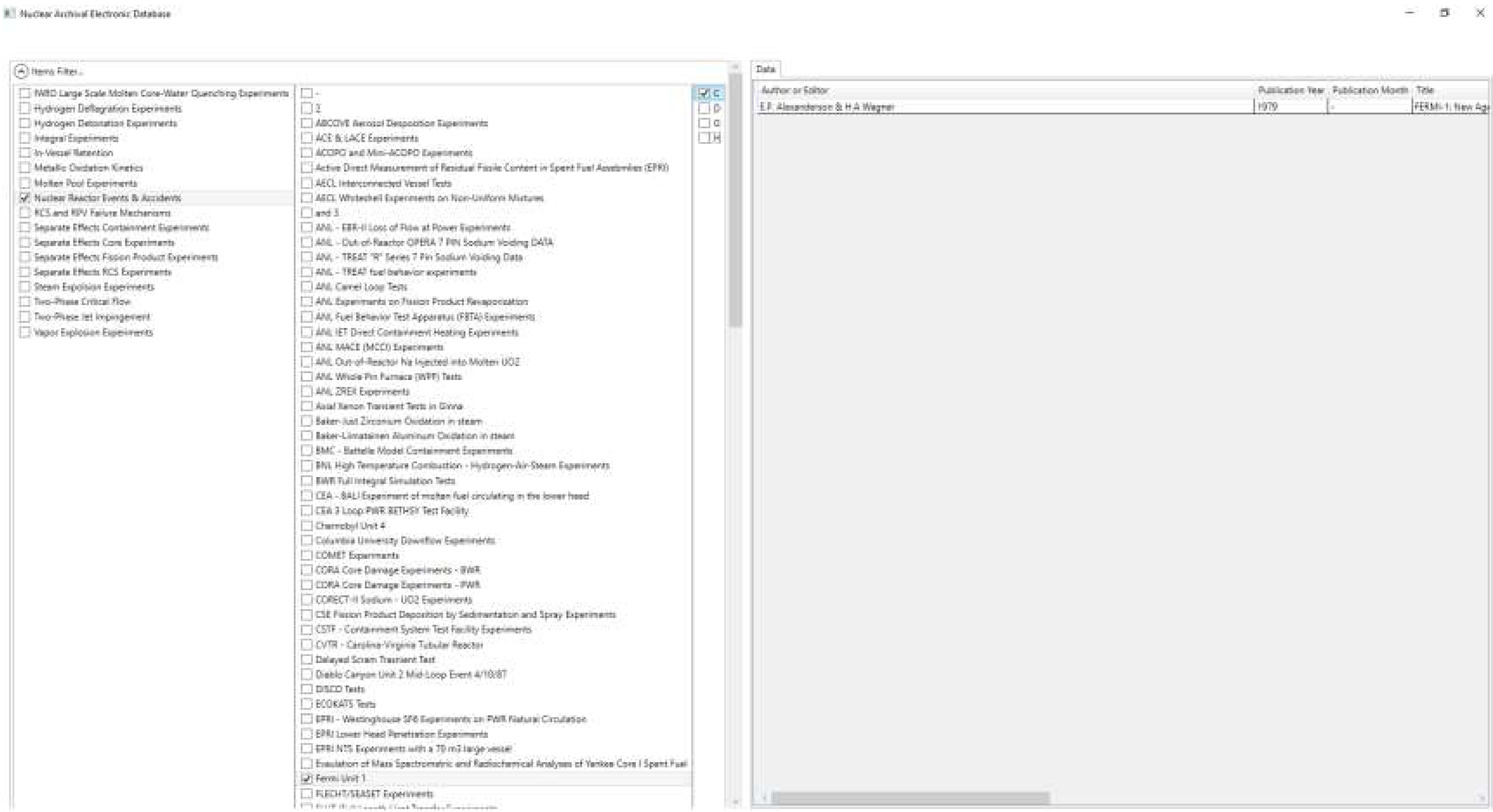


Figure 4-5 Example of Search for References Related to the Accident at FERMI Unit 1 in Data Quality Category C

5.0 A POSSIBLE NEXT STEP

This limited scope study has focused on laying a framework for preserving the results of important experimental programs for light water reactor and advanced reactor safety. This was done by researching selected experimental programs, which were considered to potentially be "at risk" for information loss and organizing the data into an electronic database. The database was developed to organize the experimental information that exists on specific topics and make it a user-friendly tool to easily locate the applicable references. The database also includes an assessment on the source and quality of the data which can potentially save a user time when attempting to locate specific information.

From these activities, it became clear there are three (3) possible improvements that stand out.

1. A possible next step would be organizing the relevant information by the reactor coolant type that the experiments represent. In fact, the reactors that have been developed throughout the world have been structured around four (4) types of coolants: (a) water (both light and heavy), (b) liquid metal, (c) gas (helium), and (d) organic fluids. Coolant characteristics have a huge influence on the design, operation, and licensing of these commercial plants. From a practical viewpoint, these influences are so important that there is little commonality between the behaviors of the reactors under operational, and possible accident, conditions. Therefore, organizing the relevant information based on this subject would be beneficial. This characterization can also be used to set the priority for including future experiments from Appendix B of Ref. 1 to ensure the most relevant data is being included in future versions of the database.

2. When considering integral experiments, there are several phenomena that need to be considered when attempting to interpret the results. Conversely, the reverse is true for experiments focused on an individual phenomenon. While the electronic database is currently oriented to provide references for a specific set of filter criteria, it will be equally important for the tool to identify those experimental programs, which focused on a single phenomenon, but which can be directly related to the integral result of several phenomena. Similarly, if the user is reviewing an integral experimental program, the tool will need to identify those phenomenological experimental programs to ensure the user is correctly interrupting the integral results.

3. One of the features that may arise when characterizing the status of an experiment and/or a nuclear accident is that some of the technical information may be archived while other aspects may be in separate papers or reports that could be in jeopardy of being lost. This was the case for the composite Fermi 1 accident evaluations, and this was also found to be the case for the Marviken, large scale, steam-water critical flow tests (Ref. 1). For those papers, reports, etc. that are already archived, this should be noted in the electronic database

as being archived by a specific organization. As discussed in the example for the Fermi 1, the American Nuclear Society publishes a book; therefore, are the organization responsible for the archived document. Additionally, ANS published one of the other papers found related to the Fermi 1 accident and is listed as being in the ANS records as an article in the Nuclear News periodical. The remaining two documents listed for the Fermi 1 accident were presented as part of a nuclear safety conference in 1967. It is suggested that these documents be scanned and added to the electronic database as important information that was not found to be part of any other archival program. In this manner, the rights of all archival organizations could be honored and those documents that are found to be outside of any such organization could be captured in the electronic database. Formalizing this approach along with the ground rules associated with what type of documents could be included in this way, could be part of a follow-on GAIN activity. This would of course include examples of papers, reports, etc. from meetings where the documents were distributed out but were not entered into a long-term archival program. A secondary benefit of this process is that a list of available sites where important data is archived and the conditions that control the access to the data can be complied for users that are not familiar with the spectrum of the archival sites that exist.

Identifying experiments based on these characteristics would be helpful in organizing the archived information for the spectrum of experimental programs that are relevant to reactor safety evaluations.

6.0 SUMMARY

The three (3) tasks stated in the SOW were addressed by:

a. A literature review on seven (7) separate experimental topics, selected from the international survey conducted during Phase-I. (Relevant information was only found on five (5) of the seven (7) proposed experimental topics.)

b. Based on the initial literature review, the experimental programs were down selected to include five (5) programs for further evaluation. As part of the further evaluation, a recommendation on how the data should be archived for each program was made.

c. Using the recommendations on how to archive the five (5) experimental programs, the beginning of a dynamic electronic database was created to begin showing how the data can be organized and categorized to benefit future generations of reactor safety experts. If the evaluation of one or more of the selected programs has already been archived, the location of the archival site was recorded in the proposed electronic data file.

With the experiences provided by this effort, the great value of having experimental data archived and easily retrievable is clear. The framework laid out as part of this effort shows that a common database can be used to organize and categorize the immense amount of reactor safety data available. The database can provide an extensive amount of information on the quality of data, reference source, and archival location. By adding user interface features within the database (filters and keyword search), a user can quickly display all available information pertaining to a specific topic. This will reduce the time required to find relevant experimental information when evaluating reactor safety on current or advanced reactor designs. To this end, we have recommended the next step for the preservation of key experimental data activity so that this preservation activity can be accomplished in a focused and cost-effective manner.

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9. Hashimoto, Kazuichiro (ed.); Japan Atomic Energy Research Inst., Tokyo (Japan); 377 p; Nov 2000; p. 216-221; SARJ-99: workshop on severe accident research, Japan; Tokyo (Japan); 8-10 Nov 1999.

10. LR. M. Elrick, et al., "Reaction Between Some Cesium-Iodine Compounds and the Reactor Materials 304 Stainless Steel, Inconel 600 and Silver, Volume II Cesium Iodide Reactions," NUREG/CR-3197/2 of 3, SAND83-0395, Sandia National Laboratories, Albuquerque, New Mexico, June 1984.

11. B. R. Bowsher, "Fission-Product Chemistry and Aerosol Behaviour in the Primary Circuit of a Pressurized Water Reactor under Severe Accident Conditions," Progress in Nuclear Energy, Vol. 20, No. 3, pp. 199-233, 1987.

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13. Rosenberg H.S., Genco J.M., Morrison D.L., "Fission Product Deposition and its Enhancement Under Reactor Accident Conditions: Deposition on Containment System Surfaces", Battelle Memorial Institute Report, BMI-1865, Columbus, 1969.

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